Jet Direction Control Using Circular Cylinder with Tangential Blowing

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We propose a tangential blowing cylinder, a type of circulation control wing, to control the direction of a jet replacing a blade or a cascade. Flow characteristics including deflection are experimentally investigated. Specifically, visualization observations, velocity distribution measurements, and the effects of momentum ratio, injection angle, and location of the cylinder on the deflection angle of the jet are analyzed. The stalling at an angle-of-attack above 20° with a single blade impedes direction control for such large angles. However, the jet may be bent to approximately 90° by using the proposed tangential blowing cylinder. The optimal injection angle for controlling the jet direction and the unsteady characteristics downstream of the tangential blowing cylinder are also determined.

Key Words: Jet Flow, Circulation Control Wing, Coanda Effect, Flow Direction Control

1. Introduction

In recent years, many studies of jets considering the Coanda effect and boundary layer control have been conducted. In particular, the circulation control wing (CCW) is attracting research attention. The CCW generates a high lift by generating circulation around the blade due to the Coanda effect created by a tangential flow from the slots on the suction side of the blade.1–3) In addition, the CCW controls circulation by adjusting the momentum of the jet injected from the slot and does not require a shape change, unlike conventional high-lift devices. Therefore, the CCW structure can be easily simplified and miniaturized, and its weight can be reduced. Moreover, the CCW can be effective for stall control, flutter, and suppression of fluid noise.

As the CCW has an extremely large lift coefficient, previous studies have focused on short takeoff, low fuel consumption, and noise reduction for short takeoff and landing.4,5) Recently, CCW technology has been used to realize short takeoff and landing of flying boats for marine rescue operations.

A tangential blowing circular cylinder can be considered as the simplest model of CCW. The tangential blow from the cylinder surface allows for the suppression of boundary
layer separation and turns the flow, thus generating lift. The tangential blowing cylinder has been investigated\(^{6-8}\) and applied to no-tail-rotor helicopters, in which the tail rotor is replaced by a tangential blowing cylinder. This structure reduces noise by eliminating the interference between the tail rotor and the main rotor. Moreover, the variable flow direction with a fixed geometrical shape may enable the application of the cylinder to turbomachinery stators, reduction of vehicle resistance, and suppression of Karman vortex in blunt bodies, among other things. The unsteady characteristics of a tangential blowing cylinder in a uniform flow are similar to the hydrodynamic characteristics of a stall when a nearby wall is present. In this case, flow oscillations differ from those caused by Karman vortices are generated.\(^{9-16}\)

To date, few studies have applied the CCW for jet direction control using thrust vectoring. In general, thrust vectoring of a propulsion unit adopts a method to either adjust the injection angle by changing the injection nozzle or add a blade or cascade to the injection outlet for adjusting the injection direction through the blade angle. In most cases, however, it is necessary to modify and adjust the geometry to change the flow direction. Therefore, most effects of CCWs (i.e., including the tangential blowing cylinder) on the flow characteristics of the primary jet remain unclear. More specifically, few studies have addressed the effects of slot angle, dimensionless primary jet width, and cylinder location (eccentricity) on flow characteristics.

To control the direction of a two-dimensional jet (i.e., primary jet), we install a tangential blowing cylinder downstream of the primary jet instead of a blade or a cascade. We aim to perform primary jet direction control by adjusting the flow blowing from the cylinder without changing the cylinder geometry. Flow visualization, pressure measurements, and velocity measurements are mainly conducted. In addition, the effects of momentum ratio, jet angle, primary jet width, and eccentricity of the cylinder installation on the jet deflection angle are analyzed. Moreover, unsteady characteristics are discussed based on velocity fluctuations measured using a hot-wire anemometer downstream of the tangential blowing cylinder.

2. Methods

2.1. Experimental setup

An outline of the experimental apparatus is shown in Fig. 1. Figure 2 shows the top view of the test section for the experiments. The test section is downstream from a wind tunnel (nozzle) and is above a plenum tank that has a blower. A circular cylinder in the test section is connected to the plenum tank by a pipe with a bell mouth. The primary jet from the nozzle produced by the wind tunnel flows across the circular cylinder. The area of the experiment square platform (i.e., acrylic plate) is 1 m\(^2\), and the outlet of the nozzle is placed next to the left center of the platform. Two aluminum plates are installed on both sides of the nozzle with a W interval. A circular cylinder with tangential blowing is installed at 200 mm to the right of the nozzle. The flow development region where the potential core exists is \(x < 6W\) in the two-dimensional jet \(^{17}\) and in this experiment, the tangential blowing cylinder installation position is \(x = 1W\). Therefore, the cylinder is in the flow development region where the potential core exists. The turbulence intensity, \(RMS_U = \sqrt{\frac{1}{N} \sum (u - \bar{u})^2 / U_p} / N\), at \(x/D = -2\), is less than 3%. The primary jet velocity is measured using the Pitot tube, a differential pressure gauge, and Matlab. The Pitot tube is connected to the differential pressure gauge, and the differential pressure gauge is connected to the computer. As shown in Fig. 2, the velocity of the primary jet is obtained as a time-averaged value of the data of the Pitot tube set at the center of the wind tunnel outlet and using Matlab. The sampling time is 50 s, and the sampling frequency is 1 Hz.

Fig. 1. Experimental apparatus.

For the jet sheet from the cylinder, the air supplied to the plenum tank by the blower exits through the slot of the circular cylinder. Figure 3 shows a schematic of the proposed circular cylinder with a diameter \(D\) of 50 mm, span length of 200 mm, and slot width \(b\) of 1 mm. Investigations of the effects of the aspect ratio of a tangential blowing cylinder on the flow characteristics around the cylinder were con-
ducted.\textsuperscript{18–21} Waka et al.\textsuperscript{20} reported that the flow at the middle span of a cylinder with an aspect ratio $l/D \geq 4$ can be considered as a two-dimensional flow by only correcting the induction angle-of-attack. Therefore, in this study, the aspect ratio was set to 4 in order to obtain a uniform jet in the span direction from the cylinder. However, as this research focuses on qualitatively clarifying the effect of the tangential blowing cylinder on the deflection characteristics of the primary jet, the induction angle-of-attack is not particularly corrected. The slot is a semicircle with a diameter of 4.25 mm and is a quarter of an ellipse with long and short axes of 49 and 30 mm, respectively. The slot corresponds to the gap between two arcs, as shown in Fig. 3. For measuring of the jet seat velocity, the flow rate is calculated from the differential pressure between the plenum tank and the bell mouth, and the velocity at the slot outlet is calculated by dividing the flow rate by the slot outlet cross-section.

A hot-wire anemometer, an I-type hot-wire probe, traversers, and Matlab are used to measure the velocity distribution at 300 mm around the cylinder. To measure the jet fluctuation at the wake of the cylinder, the measurement radius is set to 100 mm. The I-type hot-wire probe is connected to the hot-wire anemometer, and the hot-wire anemometer is connected to the computer. The movement of the hot wire on the measuring radius relies on three traversers: two control the movement in the $y$ direction and one controls the movement in the $x$ direction. There are 42 measuring points in this experiment, and the velocity of each measuring point is obtained using the averaged values. The sampling time is 20 s, and the sampling frequency is 10 kHz.

To measure the pressure on the cylinder surface, 37 static pressure holes with a diameter of 0.5 mm are distributed within $\varepsilon = 100$ to 137 mm in a spiral. For the pressure distribution measurements, a digital manometer (DMP202n12, Okano Works, measurement accuracy $\pm 0.2\%$ FS $\pm 1$ dig, time resolution 1 Hz) is applied, and the data are uploaded to the computer. The sampling frequency and sampling time are 1 Hz and 50 s, respectively, and the time-averaged pressure distribution is obtained.

Except for the experiment using a varying slot angle $\theta_j$, the slot angle is set to 90° from the front edge. To evaluate the effects of the slot angle and the circular cylinder eccentricity, the nozzle width is fixed to 200 mm. Except for the experiment involving circular cylinder eccentricity, the location of the nozzle,

$$\varepsilon = \frac{2d}{(W - D)},$$

is fixed at $\varepsilon = 0$ for the primary jet width $W$.

2.2. Experimental evaluation

Experiments were conducted considering the Reynolds number range $Re = 2.0 \times 10^3$–$3.0 \times 10^4$, dominant frequency of Karman vortex $St \approx 0.2$, and expressions

$$Re = \frac{U_p D}{V},$$

and

$$St = \frac{f D}{U_p}.$$ (3)

The main evaluation parameters are nozzle width $W$, slot angle $\theta_j$, eccentricity of circular cylinder $\varepsilon$, and momentum coefficient of jet $C_\mu$, which is defined as

$$C_\mu = \frac{V_j^2 b}{\frac{1}{2} \rho U_p^2 W}.$$ (4)

To evaluate the influence of nozzle width (i.e., primary jet width), we considered values of 200, 150, and 100 mm. The experiments using slot angles were divided into two parts. First, we analyzed the results of slot angles of 0, 90, 180, and 270° to select the best angle. Then, subsequent slot angle experiments were conducted based on the optimal angle. These experiments considered slot angles of 70, 110, and 130°. To evaluate the influence of the circular cylinder position, the eccentricity rate $\varepsilon$ was set to 0 and $\pm 1.3$. Given the large influence of momentum ratio, the momentum coefficient was considered as a parameter in every experiment.

In this study, the pressure coefficient $C_p$ is defined as the cylinder surface pressure minus the atmospheric pressure and then divided by the main flow pressure.

$$C_p = \frac{P - P_a}{0.5 \rho U_p^2},$$ (5)

where $P$ is the surface pressure of the cylinder, $P_a$ is the atmospheric pressure, and $\rho$ is the density of the fluid. The estimated separation point angle $\theta_j$ is obtained from the pressure distribution using the method of Okamoto et al.\textsuperscript{3}.

The Coanda effect induces a tendency for the primary jet to deviate from its original direction and flow on the surface of the circular cylinder. When the flow separates from the circular cylinder, the lift coefficient decreases, and the pressure coefficient $C_p$ increases. Therefore, separation is the critical point where the pressure coefficient gradually increases and then stabilizes.

For error analysis, we acquired measurements using a digital monitor and a hot-wire anemometer (Kanomax, Osaka, Japan). From 42 acquired datasets (i.e., 200,000 datapoints per set), the highest standard deviation of variation obtained
from the anemometer is 0.0091. In addition, the precision
and absolute error of the digital monitor are ±0.2% and
0.5 Pa, respectively. In the experimental results of this paper,
the highest standard deviation in \( C_P \) is 0.923 for
\( C_\mu = 0.364 \). In addition, the highest standard deviation in \( \theta_k \)
is 6.98 for \( C_\mu = 0.030 \), and that in the lift coefficient, \( C_L \), for
\( \theta_j = 0^\circ \) and \( C_\mu = 0.364 \) is 0.87.

Deflection angle \( \theta_k \) represents the jet center of the fluid. To
accurately obtain \( \theta_k \) under different momentum coefficients,
the centroid of the area of the velocity distribution area
should be the jet center of the fluid, with its angle being \( \theta_k \).

Figure 4 illustrates the calculation for determining the veloc-
ity distribution centroid. The graph of velocity distribution is
not closed, because the dotted curve parallel to the arc of the
measurement point is generated under different momentum
coefficients. To ensure a small error, the spacing of this equi-
distant curve was placed at 30% of the velocity distribution
apex. The centroid of the velocity distribution area is given by

\[
\theta_k = \frac{1}{\int_{\theta_1}^{\theta_2} |U| \, d\theta} \int_{\theta_1}^{\theta_2} |U| \theta \, d\theta.
\]  

(6)

3. Results and Discussion

3.1. Optimal injection angle and jet widths

The obtained jet for \( \theta_j = 90^\circ \) is shown in Fig. 5 for \( C_\mu \) of
0 (Fig. 5(a)), 0.068 (Fig. 5(b)), and 0.364 (Fig. 5(c)). In
Fig. 5, vortices can be seen at the velocity shear layer of
the primary jet as Kelvin–Helmholtz instability. Since this
kind of instability occurs locally, it can be considered that
the effects on the jet deflection characteristics are not large.
The jet sheet generated on the cylinder surface flows along
the cylinder due to the Coanda effect. The deflection angle
of the primary jet increases as the momentum coefficient in-
creases, being qualitatively consistent with the results from
previous studies. As the jet sheet adheres to the cylinder sur-
face, separation of the boundary layer on the slot is sup-
pressed, and the primary jet is drawn into the jet sheet. As
a result, the primary jet is deflected to the opposite side of
the slot.

Figure 6 shows the pressure distribution on the cylinder
surface as the pressure coefficient according to the angle
from the front edge for different momentum coefficients.
At \( \theta = 90^\circ \), the jet flows along the cylinder surface, and as
\( C_\mu \) increases, the pressure coefficient decreases as the cen-
trifugal force downstream of the slot increases. The jump in
the pressure coefficient value immediately after the slot may be
due to local vortex formation, because the injection angle
is approximately 18.5°.

Figure 7 shows the jet sheet separation point angle accord-
ing to the momentum coefficient. The estimated separation
point is obtained applying the method of Okamoto et al.\(^3\)
and not strictly determined from the velocity gradient. Angle
\( \theta_s \) recedes as the momentum coefficient increases, being mostly
consistent with the experimental results of Okayasu et al.\(^6\)
The lift coefficient, $C_L$, is obtained as the components vertical to the primary jet of the integral value of the pressure distribution on the cylinder surface as determined in previous research. $^{5-7}$

$$C_L = -\frac{1}{2} \int_0^{2\pi} C_P \sin \theta \, d\theta.$$  \hspace{1cm} (7)

$C_L$ is shown in Fig. 8, presenting an increasing trend according to the momentum coefficient. This result mostly agrees with previous experimental results using a tangential blowing cylinder in a uniform flow. For a general single blade, as stall occurs at an angle-of-attack of $\alpha > 20^\circ$, coefficient $C_L$ does not exceed 2. On the other hand, a large $C_L$ is obtained for the tangential blowing cylinder (Fig. 8). Therefore, we consider that the primary jet must have undergone a large change in momentum and consequently its traveling direction.

Figure 9 shows the velocity distributions measured using a hot-wire anemometer on an arc with radius $r = 300$ mm according to angle $\theta$. The dimensionless velocity is obtained by dividing the absolute value of the velocity by the primary jet velocity. For $C_\mu = 0$, the velocity distribution is equivalent to that of a general wake of a cylinder without a blowing slot (Fig. 5(a)). A velocity defect and symmetric velocity distribution are observed in the range $170 < \theta < 190^\circ$ for $C_\mu = 0$. As $C_\mu$ increases, the symmetry breaks down, and the center of the primary jet shifts to the right, as shown in Fig. 9. For $C_\mu = 0.068$ (Figs. 5(b) and 10(d)), the velocity defect does not occur, and a deflected jet similar to a Gaussian distribution appears. Furthermore, within this condition range, a larger $C_\mu$ implies a higher maximum speed.

Figure 10 shows the spectral distribution of the velocity fluctuation measured using the hot-wire anemometer. For $C_\mu = 0$ (Fig. 10(a)), a velocity fluctuation due to the Karman vortex occurs around $St = 0.2$. For $C_\mu = 0.009$ (Fig. 10(b)), the dead water area behind the cylinder becomes smaller and $St$ increases slightly. For $C_\mu = 0.030$ (Fig. 10(c)), the dead water region behind the cylinder almost disappears, the peak velocity fluctuation spectrum becomes extremely small, and $St$ is approximately 0.3. For $C_\mu = 0.068$ (Fig. 10(d)), no clear peak can be observed in the spectrum distribution. As described above (Fig. 10), no velocity defect occurs for $C_\mu = 0.068$. Therefore, Karman vortices generated by the winding of the velocity shear layer in the velocity defect area disappear. The lack of Karman vortices at a certain flow rate in the tangential blowing cylinder is consistent with the results obtained by Yoshida et al.$^{16}$

The deflection angle of the jet is $\theta_c = \Delta \theta_t + 180^\circ$.

To investigate the effect of the slot angle (i.e., injection angle) on the flow characteristics of the primary jet, we evaluated typical flow patterns of $C_\mu = 0.187$ for $\theta_t = 0, 90, 180,$ and $270^\circ$, obtaining the results shown in Fig. 11(a) to (d), respectively. Deflection angle $\theta_t$ depends on the slot an-
gle, and the primary jet is most deflected at $\theta_j = 90^\circ$, whereas at $\theta_j = 180^\circ$, the jet splits into two.

Figure 12 shows the relation between $C_{\mu}$ and $C_L$ for $\theta_j = 0, 90, 180, \text{ and } 270^\circ$. The lift coefficient, $C_L$, in this figure is defined by the integral of the cylinder surface pressure distribution. For $\theta_j$ of 180 and 270$^\circ$, $C_L$ depends on $C_{\mu}$ but does not increase with it. Therefore, these angles are not suitable for primary jet direction control. On the other hand, for $\theta_j$ of 0 and 90$^\circ$, $C_L$ increases with $C_{\mu}$, with the maximum $C_L$ at $\theta_j = 90^\circ$ being higher than that at $\theta_j = 0^\circ$. Therefore, a larger primary jet deflection is expected at $\theta_j = 90^\circ$. Below, we analyze the flow field around $\theta_j = 90^\circ$ in more detail.

Figure 13 shows the relation between $C_{\mu}$ and the deflection angle from the back edge, $\Delta \theta_c$, around $\theta_j = 90^\circ$, where $\Delta \theta_c$ is the center of gravity of the jet obtained from the time-
averaged velocity distribution measured at $r = 300$ mm. For $\theta_j = 70 \sim 130^\circ$, $\Delta \theta_a$ increases with $C_\mu$. The result for $\theta_j = 90^\circ$ corresponds to the outline of the curve of the lift coefficient and separation point. In the evaluated range, the maximum $\Delta \theta_a$ increases with $\theta_j$, being more advantageous to increase $\theta_j$ when a large deflection angle is expected from 70 to 130$^\circ$.

For $\theta_j = 130^\circ$, the value of $\Delta \theta_a$ sharply increases around $C_\mu = 0.1$. As mentioned above, for $C_\mu = 0$, the separation point is around $90^\circ$, and at $\theta_j = 130^\circ$, the approximate separation point angle is $90 < \theta_s < 130^\circ$ for $C_\mu < 0.1$. In this region, the pressure drop due to jet entrainment appears with increasing $C_\mu$, and the pressure gradient on the cylinder surface becomes negative, while the separation point gradually shifts downstream. However, around $C_\mu = 0.1$, if the angle of separation point, $\theta_s$, exceeds $130^\circ$, the separation point suddenly shifts downstream due to the inertia of the jet sheet. Consequently, at $\theta_j = 130^\circ$, the deflection angle presents a sharp increase around $C_\mu = 0.1$. Therefore, for smooth primary jet direction control, it is appropriate to set a blowing slot at the separation point of $C_\mu = 0$ (around $\theta = 90^\circ$). From these results, it is possible to control deflection angle $\Delta \theta_a$ from 0 to approximately 90$^\circ$ only by adjusting the momentum coefficient without changing the structure shape by using the tangential blowing cylinder downstream of the two-dimensional plane jet.

Figure 14 shows the relation between $C_\mu$ and $\Delta \theta_a$ for various dimensionless primary jet widths, $W/D$. No clear difference is observed among $W/D$ of 2, 3, and 4. The deflection characteristics of the primary jet can be arranged by the ratio of the momentum of the primary jet to the momentum of the blowing jet seat, $C_\mu$, regardless of $W/D$.

3.2 Eccentricity of cylinder

Figures 15 and 16 show the effects of eccentricity on the flow characteristics for $C_\mu = 0.364$. Figure 15 shows the velocity distributions for $\varepsilon$ of $-1.3$ (see Fig. 16(a)), 0 (see Fig. 5(c)), and 1.3 (see Fig. 16(b)). The angle at maximum jet velocity slightly increases in order for $\varepsilon$ of 1.3, 0, and $-1.3$. Thus, for $-1.3 \leq \varepsilon \leq 1.3$, the deflection angle increases as $\varepsilon$ decreases.

The results for $\varepsilon$ of $-1.3$ (Fig. 16(a)) and 1.3 (Fig. 16(b)) show a clear difference in the position of the separation point, which is larger for $\varepsilon = 1.3$ than for $\varepsilon = -1.3$. Moreover, for $\varepsilon = 1.3$, the flows passing through the upper- and lower-cylinder surfaces collide. Consequently, although the separation point angle is large, there is no notable difference between the deflection angle for $\varepsilon = 1.3$ shown in Fig. 16(b) and that for $\varepsilon = 0$ shown in Fig. 5(c). In addition, the deflection angle for $\varepsilon$ of $-1.3$ is strictly higher than that at $\varepsilon$ of 1.3 and 0.

4. Conclusion

To control the direction of a two-dimensional jet, we install a tangential blowing cylinder downstream of the primary jet and experimentally evaluate the flow characteristics around the cylinder. Flow visualization, time-averaged pressure measurements on the cylinder surface, and time-averaged velocity and velocity oscillation measurements are analyzed. From the proposed cylinder and experimental results, we can draw the following conclusions:

1) The flow direction of the primary jet depends on the momentum coefficient $C_\mu$. The deflection angle $\Delta \theta_a$ can be controlled from 0 to approximately 90$^\circ$ in the parameter range considered in this study.

2) At slot angle $\theta_j = 90^\circ$, the curves of lift coefficient, separation point, and deflection angle according to the momentum coefficient are consistent. To smoothly control the deflection angle, it is necessary to precisely control
the position of the separation point.

3) The slot angle evaluation shows that the deflection characteristics depend not only on coefficient $C_{\mu}$ but also on slot angle $\theta$. For stepless control, it seems appropriate to set a blowing slot at the separation point for $C_{\mu} = 0$: that is, around $\theta = 90^\circ$.

4) The deflection characteristics of the primary jet can be summarized by $C_{\mu}$, which is a function of the nozzle width $W$ of the primary jet.

5) The effect of the eccentricity rate $\varepsilon$ on the deflection characteristics is mostly negligible, but a larger deflection can be expected for $\varepsilon = -1.3$ at a given $C_{\mu}$.

6) As a cylinder with tangential blowing in a uniform flow, the cylinder downstream of the primary jet can suppress Karman vortices by adjusting the momentum of the jet sheet.

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