An Attempt for Suppression of Wing-Tip Vortex Using Plasma Actuators*

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Abstract
Influence of the flow induced by dielectric barrier discharge (DBD) plasma actuators on the wing-tip vortex is investigated numerically and experimentally. The plasma actuators are installed on the suction side of the NACA0012 airfoil and operated in blowing and suction modes. For the numerical simulation, direct numerical simulation (DNS) based on the finite-difference immersed-boundary method is used. The DNS shows that the circulation parameter, which measures the strength of wing-tip vortex, is reduced by blowing as well as suction. At the same time, however, the lift-to-drag ratio is found to decrease by the actuation. In the experiment, a wing model with plasma actuators is set inside the wind tunnel and the velocity fields are measured using a PIV system. Although suppression of wing-tip vortex is not confirmed due to insufficient strength of actuation and insufficient length of measurement area, the change of streamwise mean velocity profile is found to be similar to that of DNS.

Key words: Plasma Actuator, Flow Control, Wing-Tip Vortex, PIV Measurement, Numerical Simulation

1. Introduction
Recently, dielectric-barrier-discharge plasma actuators (hereafter referred to as DBD-PA) have attracted increasing attention as novel airflow control devices. Structure of a DBD-PA is very simple: a thin dielectric layer is sandwiched by two electrodes. Plasma is generated between the asymmetrically arranged two electrodes, one being exposed to the atmosphere and the other covered by dielectric material, when high-frequency high voltage AC is imposed between them. The time-averaged body force is directed from the exposed electrode to the covered one, which generates a unidirectional flow. The characteristics of induced flow depend on various parameters, such as the amplitude and frequency of the charged voltage, the widths and arrangements of electrodes, and the thickness and material of dielectric layer. The magnitude of the induced velocity is usually less than 10 m/s. Although it is believed that the generation of unidirectional flow is due to the asymmetric discharge between the open and covered electrodes, the detailed mechanism of DBD-PA is now intensively studied both experimentally and numerically.

DBD-PAs have been widely tested due to the following merits: (1) light-weight, no moving part; (3) very thin, small aerodynamic effect; and (3) fast response. The previous studies include drag reduction in wall-turbulence and aerodynamic noise suppression as well as various controls of flow around a wing such as separation.
As for the flow around a wing, there is an issue of wing-tip vortex in addition to the separation. The wing-tip vortex (WTV) is a strong streamwise vortex generated from the wing-tip and its characteristics have extensively been studied. The existence of WTV is a major cause of the restriction of the interval of take-off/landing of aircrafts. Suppression of WTV is therefore preferable considering the increasing demand of air transportation. It is also desirable in terms of environmental concerns to reduce the fuel consumption by suppressing WTV while keeping the wing performance.

Passive control of WTV, such as winglet, has already been used in practice. Active control of WTV is being studied to attain larger effects. Figure 1 shows an example of such active control using blowing/suction from slots. Both steady and periodic blowing/suction controls have been reported. The experimental study using a steady blowing reports that the direction and magnitude of blowing largely affect the lift and the development of WTV. On the other hand, the study using a steady suction reports suppression of WTV near the trailing edge.

Practical implementation of such blowing/suction slots is not easy. Due to the above-mentioned merits, DBD-PAs may be used more easily if similar effects can be obtained. It is also expected to apply MEMS-fabricated DBD-PA to suppress WTV around small flying objects such as micro-aerial vehicles (MAVs).

In the present study, the effect of the spanwise blowing/suction generated by the DBD-PAs on WTV is investigated by means of direct numerical simulation (DNS) and wind-tunnel experiment. In the DNS, a flow around a wing is simulated with the body force induced by DBD-PAs. We also conducted a PIV measurement with a similar configuration in order to confirm the effect of DBD-PA. The effect of the blowing/suction on the generation and development of WTV is studied in both simulation and experiment.

2. Computational Method

2.1 Computational Condition and Method

We consider the flow around an NACA0012 airfoil as shown in Fig. 2. We impose a uniform velocity at the inlet, the convective boundary condition at the outlet, free-slip condition on the top and bottom boundaries, and the periodic boundary condition in the spanwise direction, respectively. The Reynolds number based on the uniform velocity $U_\infty$ and the chord length $c$ is $Re = U_\infty c / \nu = 3000$. The attack of angle is fixed at $10^\circ$.

Direct numerical simulation (DNS) is used in the present study. The DNS code is based on that developed for channel flow and adapted to the present boundary conditions. The energy conservative second order finite difference method, the third order low-storage Runge-Kutta/Crank-Nicolson scheme, and the higher order delta-form fractional step method are used for the spatial discretization, the time integration, and the velocity-pressure coupling, respectively. The two-dimensional (i.e., spanwise and streamwise) fast
Fourier transform with the mirror image\cite{28} is used to solve the Poisson equation in the non-periodic geometry. The Cartesian structured grid is used and the no-slip boundary condition on the wing surface is treated by using the immersed boundary method\cite{29}.

The size of computational domain is \((12, 2, 6)\) in the streamwise \((x)\), vertical \((y)\), and spanwise \((z)\) directions with the length being nondimensionalized by using the chord length \(c\), and the corresponding number of computational cells is \((256, 96, 128)\). The grid is uniform in \(x\) and \(z\) directions \((\Delta x = 0.047, \Delta z = 0.047)\), while nonuniform in \(y\) direction \((\Delta y_{\text{min}} = 0.004)\) so as to resolve the vortical structure near the wing. The time step \(\Delta t\) is chosen so that the Courant number \(U_\infty \Delta t/\Delta x\) does not exceed 0.5. These computational conditions have been chosen similarly to those used by Taira and Colonius\cite{30} who studied the flow around a flat plate: the spatial and temporal resolutions are considered sufficient. Note that the small aspect ratio and the low Reynolds number assumed in the present study, which were also chosen by referring to Taira and Colonius\cite{30} are impractical for real aircrafts. However, we chose those conditions so as to study the primary effect of actuation on WTV with a reasonable computational cost.

### 2.2 Control Method

In order to evaluate the influence of DBD-PA, the induced body force \(f_{\text{PA}}\) is taken into account. The governing equations are the incompressible continuity and the Navier-Stokes equations with the body force term, i.e.,

\[
\nabla \cdot \mathbf{u} = 0, \quad (1)
\]

\[
\frac{\partial \mathbf{u}}{\partial t} = -\nabla \cdot (\rho \mathbf{u} \mathbf{u}) - \frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f}_{\text{PA}}. \quad (2)
\]

Note that the numerical forcing terms used in the immersed boundary method are not displayed in Eqs. (1) and (2).

The actual time-scale of the body force induced by the DBD-PA is micro to milliseconds. In the present study, however, a time-average body force model by Shyy et al.\cite{32} is adopted to save the computational cost. This model assumes the generation of plasma in the triangular region as shown in Fig. 3. The electric field is assumed to linearly decay according to the distance from the origin. The time-averaged body force vector is modeled as

\[
f_{\text{PA}} = f_{\alpha} e \Delta V \mathbf{E} \delta, \quad (3)
\]
where \( f \), \( \alpha \), \( \rho_c \), \( e_c \), and \( \Delta t \) denote the AC frequency, the collision coefficient, the charge density, the elementary charge, and the time interval in which the body force works, respectively. The electric field vector \( \mathbf{E} \) is modeled as

\[
\mathbf{E} = \begin{pmatrix}
E_{k_1} \\
\sqrt{k_1^2 + k_2^2} \\
\sqrt{k_1^2 + k_2^2}
\end{pmatrix}
\]

and \( \delta \) is a flag which is unity if the field intensity \( E = |\mathbf{E}| \) is larger than the breakdown intensity \( E_b \), or zero otherwise. The field intensity at position \((\xi_1, \xi_2)\) is given by

\[
E(\xi_1, \xi_2) = E_0 - k_1\xi_1 - k_2\xi_2.
\]

As shown in Fig. 4, three plasma actuators are placed near each wingtip on the suction side. As for the direction of body force, Suction (inward, blue arrows in Fig. 4) and Blowing (outward, red arrows in Fig. 4) are considered. The case without actuation is referred to as No Control (NC). The model parameters are set to be \( E_0 = 2.26 \times 10^7 \) V/m, \( E_b = 3 \times 10^5 \) V/m, \( a = 1 \) mm, \( b = 2 \) mm, \( k_1 = (E_0 - E_b)/a \), and \( k_2 = (E_0 - E_b)/b \). The other parameters are chosen so that the induced velocity becomes roughly 25% of the freestream velocity, which is the maximum azimuthal velocity of WTV right downstream of the trailing edge. The actual spanwise velocity near the actuators is determined as the result of interaction with surrounding flow field. Figure 5 shows the resultant spanwise velocity in a cross-section above the actuators. In Blowing case (Fig. 5(a)), the induced velocity is about 20% of...
freestream velocity near the first and second actuators; while it reduces at the wingtip to about 10% of freestream velocity because the induced velocity is opposed by the azimuthal velocity of WTV. In Suction case (Fig. 5(b)), in contrast, the spanwise velocity at the wing-tip is increased up to 38% of freestream velocity.

3. Computational Results and Discussion

3.1 Lift and Drag Coefficients

Figure 6 shows the time traces of lift coefficient $C_L$, drag coefficient $C_D$, and lift-to-drag ratio $C_L/C_D$ in a time period after the flow has reached the statistically steady state. The lift and drag are both computed by the summation of the pressure and frictional contributions. The pressure contribution is computed by the integration over the wing surface with a piecewise-linear shape approximation; the frictional contribution, which is smaller than the pressure contribution, is computed on the surface with a stepwise shape approximation. In Suction case, both the lift and drag coefficients are found to decrease (Figs. 5(a) and (b)) resulting in the decrease of lift-to-drag ratio (Fig. 5(c)). In Blowing case, too, both the lift and drag coefficients decrease, suggesting deterioration of wing performance; as compared to Suction case, however, the lift-to-drag ratio is less decreased because the reduction of drag is more pronounced that of lift. The relatively large amplitude of periodic variation observed in both lift and drag can be attributed to the two-dimensional vortex shedding due to the low Reynolds number (as will be observed in Fig. 7). The amplitude of variation is found to decrease in both Blowing and Suction cases.

3.2 Flow Modification

Figure 7 visualizes the vortical structure identified by using the second invariant of deformation rate tensor $Q$ and the streamwise velocity and cross-sectional velocity vectors in the $x/c = 0.5$ cross-section. The left figures confirm that the WTV structure in far downstream region is significantly weakened in Blowing case, while it becomes thinner and more straight in Suction case. The right figures show that in NC case a vortex is generated by roll-up; in Suction case the velocity deficit region shrinks; and in Blowing case the vortex is distorted.
Fig. 7 Flow structures: left, instantaneous vortical structures; right, mean streamwise velocity (color) and cross-sectional velocity (vectors) at x/c=0.5: (a) no control; (b) suction; (c) blowing.

Fig. 8 Streamwise velocity and pressure at x/c=0.5: (a) mean streamwise velocity U; (b) mean pressure P.

Figure 8 shows the mean streamwise velocity U and the mean pressure P as functions of y. The streamwise location is x/c = 0.5 and the spanwise location is the vortex center in each case. The vortex center is defined as the location where the mean cross-sectional velocities V and W simultaneously become zero. As can be seen in Fig. 8(a), the velocity deficit,
which is 42% of streamwise velocity in NC case, is largely modified by the actuation. In Suction case the velocity deficit increases up to about 50% of freestream velocity and the vortex diameter becomes smaller, resulting in larger velocity gradient inside the WTV. In Blowing case, in contrast, the velocity deficit is not much changed from that in NC case. The pressure, however, is much recovered (Fig. 8(b)).

Figure 9 shows the mean vertical velocity $V$ as a function of $z$ and the mean spanwise velocity $W$ as a function of $y$. Again, the streamwise location is $x/c = 0.5$ and the vertical or spanwise location is the vortex center in each case. The figure indicates that the maximum velocities, the vortex diameter, and the location of vortex center are modified by the actuation. In particular, the azimuthal velocity ($V$ and $W$) is significantly reduced. Figure 10 illustrates the schematic shape of WTV in each case, drawn based on the velocity profile of Fig. 9. In NC case, the WTV is elongated in $z$ and swollen in $+y$ and $-z$ directions. Although similar trend is observed in Blowing and Suction cases, too, the vortex diameter is found to increase in Blowing case and decrease in Suction case.

Figure 11 shows the locations of vortex centers at $x/c = 0.25$, 0.5, and 1.0 cross-sections. In NC case, the vortex center moves to $-z$ direction as it goes downstream. This trend is in
accordance with the previous experiment. Although the basic behavior is similar in the actuated cases, the vortex center moves toward the wing surface in Suction case and it moves away from the surface in Blowing case. This is due to the direction of induced flow: namely, in Suction case the induced flow assists the roll-up, while in Blowing case it opposes to the roll-up.

Figure 12 compares the circulation parameter $\Gamma/(U_\infty c)$. Since it is known that the value of circulation depends on the size of integration region, we define $\Gamma = 2\pi RV_\theta$ (where $R$ is the vortex radius where the azimuthal velocity $V_\theta$ takes the maximum value) here for convenience. In suction case, the circulation parameter is found to reduce by about 20% at the downstream location of $x/c = 1.0$, which is similar to the previous study using suction slots. In Blowing case, in contrast, although it slightly increases at $x/c = 0.5$ possibly due to direct addition of momentum by the actuation, about 10% reduction at the downstream location of $x/c = 1.0$ is observed. Therefore, according to the circulation parameter, the WTV is weakened in both Blowing and Suction cases.

The change of circulation parameter in downstream region can be explained by the mean vorticity profile as shown in Fig. 13. In Suction case, the vorticity in the central region is increased, but its contribution to the circulation is minor. The vorticity away from the center, which has larger contribution, is decreased. In Blowing case, although the distribution is slightly widened, the overall vorticity magnitude is decreased. These modifications can also be explained by the directional relationship between the induced flow and the roll-up as discussed above.

4. Wind-Tunnel Experiment

4.1 Standpoint of Present Experiment

Preliminary experiment has been conducted to confirm the effect observed in the numerical simulation. Due to the restriction of equipments, however, the flow conditions are different from those assumed in the simulation. The induced velocity in the experiment is about 10% of freestream velocity, in contrast to about 25% in the simulation. The Reynolds number is two decades larger than that used in the simulation. We leave the exact comparison as a future work and here we make a qualitative comparison of the effect of DBD-PA on WTV.

4.2 Experimental Setup

Particle Image Velocimetry (PIV) is used to measure the velocity distribution near the wing-tip. Figure 14 illustrates the schematic of the experimental setup. The 580 mm-long test section of 200 mm × 200 mm cross-section is attached to the open blowing wind-tunnel. The wing model was installed in the test section. The turbulence level is less than 0.5% at freestream velocity over 10 m/s. The freestream velocity was fixed at $U_\infty = 11$ m/s and the Reynolds number based on the freestream velocity and the chord length is $Re_c = U_\infty c/\nu = 1.44 \times 10^5$. The angle of attack is 10°. The wing model is an NACA0012 with the
Fig. 15 Dimensions of plasma actuator used in experiment.

Fig. 16 PA Configuration (experiment).

semispan length of \( b = 100 \) mm and the chord length of \( c = 200 \) mm. The PIV measurement was made in \( x-z \) cross sections by traversing \( y \) in the range of \(-15 \leq y \leq 35 \) mm with 5 mm interval (i.e., 11 cross sections in total). Ensemble average was made using 50 samples for each cross section. We used the PIV system at AIST, which consists of a double pulse Nd-YAG laser (25 mJ/pulse, New Wave Research Co. Ltd., MiniLaser-II, 20 Hz), a 1280 × 1024 pixel cross-correlation camera (TSI, PIVCAM13-8). The pulse interval is 100 \( \mu \)s. The repetition frequency is 3.75 Hz. Seeding was done by atomizing dioctyl sebacate (DOS) into about 1 micron droplets using a Raskin nozzle.

Figure 15 shows the schematic of DBD-PA used in the experiment. Figure 16 explains their installation positions on the wing. Copper tape (Teraoka, No. 8321, 0.09 mm thick) and polyimide tape (Nitto, No. 360UL, 0.09 mm thick) are used for the electrodes and dielectric, respectively. The widths of the upper and lower electrodes are \( w_1 = 6 \) mm and \( w_2 = 12.5 \) mm, respectively. According to Forte et al., these widths maximize the induced velocity. Similarly to the numerical simulation in the previous sections, three DBD-PAs are installed near the wing-tip on the suction side so that spanwise flow is induced. Blowing and Suction cases are examined. The DBD-PAs are driven by using a high-voltage high-frequency power supply (KI Tech., PSI-PG1040F). The root-mean-square voltage is 4 kV and the AC frequency is 5 kHz. The waveform is quasi-square. The induced velocity is about 1 m/s.

4.3 Experimental Results and Discussion

Figure 17 shows the variation of vortex center. Similarly to the computational result (Fig. 11), the vortex center moves to \(+y, -z\) direction as it goes downstream. The change from NC case, however, is found to be different from the simulation: in Blowing case the vortex center shifts in \(-y, +z\) direction, in Suction case it does not change.

Figure 18 shows the spanwise mean velocity \( W \) in an \( x-z \) cross-section crossing the vortex center. In Blowing case the generation point of WTV is shifted toward downstream, which suggests that the generation of WTV is suppressed by Blowing. In further
downstream region, however, the WTV is found to develop to the same size as that in NC case. Namely, the suppression of WTV by Blowing is merely local: the development rate in the downstream region is, in turn, increased.

Figure 19 shows the mean streamwise velocity $U$ as a function of $y$ near the vortex center at $x/c = 0.5$. Similarly to the computational result (Fig. 8), the vortex center in Blowing case is shifted in $+y$ direction without changing the size of velocity deficit region, and the velocity deficit in Suction case is slightly enhanced.

Figure 20 shows the mean spanwise velocity $W$ as a function of $y$. Similarly to the simulation, there is no significant difference between NC and Suction cases. In Blowing case, however, the spanwise velocity is found to increase unlike the simulation. This discrepancy may be due to that the induced velocity is insufficient in the experiment so that it could not oppose the roll-up.

Figure 21 compares the circulation parameter $\Gamma/(U_\infty c)$. In the experiment, the circulation is evaluated by using the maximum spanwise velocity $|W_{\text{max}}|$ and the vortex diameter $R$, as $\Gamma = 2\pi R |W_{\text{max}}|$. The effect of actuation is found to be smaller than that observed in the numerical simulation. In Blowing case, the circulation parameter is found to increase from $x/c = 0.25$ to $x/c = 0.5$, which is qualitatively in accordance with the simulation result. No significant change is observed in Suction case. Again, this may be due to the insufficient induced velocity achieved in the experiment.
5. Conclusions

Toward suppression of wing-tip vortex (WTV) using the plasma actuator (PA), direct numerical simulation was performed to investigate the effect of flow induced by PAs on the WTV. Although the lift-to-drag ratio decreases, the WTV is found to be suppressed by both Blowing and Suction. From the flow modification, the mechanism of WTV suppression is different between Blowing and Suction cases. In Blowing case, the vorticity itself is decreased by the flow opposing the roll-up. In suction case, the vortex diameter is decreased by the induced flow supporting the roll-up.

A wind-tunnel experiment of the similar configuration was also conducted. Due to the restriction of equipment, the actuation amplitude was insufficient and the measurement could not be conducted in the downstream region of $x/c = 1$ where significant reduction of circulation parameter was observed in the numerical simulation. In major statistical properties such as the velocity deficit and the circulation parameter, however, the observed trends were qualitatively in accordance with those obtained in the numerical simulation.

In the present study, we made a basic investigation of the possibility to suppress WTV by using PA. Systematic studies (both numerical and experimental) varying the freestream velocity, the arrangement and amplitude of PAs and so on are needed toward practical applications, which are left for future work.

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