

Article

Dynamic Stall Control around Practical Airfoil Using Nanosecond-Pulse-Driven Dielectric Barrier Discharge Plasma Actuators

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Abstract: The flow control effects of a nanosecond-pulse-driven dielectric barrier discharge plasma actuator (ns-DBDPA) in dynamic stall flow were experimentally investigated. The ns-DBDPA was installed on the leading edge of an airfoil model designed in the form of a helicopter blade. The model was oscillated periodically around 25% of the chord length. Aerodynamic coefficients were calculated using the pressure distribution, which was obtained by the measurement of the unsteady pressure by sensors inside the model. The flow control effect and its sensitivity to pitching oscillation and ns-DBDPA control parameters are discussed using the aerodynamic coefficients. The freestream velocity, the mean of the angle of attack, and the reduced frequency were employed as the oscillation parameters. Moreover, the nondimensional frequency of the pulse voltage, the peak pulse voltage, and the type and position of the ns-DBDPA were adopted as the control parameters. The result shows that the ns-DBDPA can decrease the hysteresis of the aerodynamic coefficients and a flow control effect is obtained in all cases. The flow control effect can be maximized by adopting the low nondimensional frequency of the pulse voltage.

Keywords: flow control; dynamic stall; plasma actuators; nanosecond pulse discharge; pressure measurement

1. Introduction

A dynamic stall occurs when an airfoil, such as a helicopter blade, experiences unsteady motion beyond a static stall angle. In a helicopter flight environment, the blade has to change the angle of attack to keep the lift symmetrical when the blade moves between the advancing and retreating sides. The dynamic stall is characterized by large shedding and passage vortex structures, called dynamic

stall vortices, and flow separation and attachment is delayed [1]. This phenomenon is an active research topic in fluid dynamics and helicopter engineering [1–4]. Effective control of the dynamic stall flow will not only improve the aerodynamic performance of the blade, but also make it simpler to design the blade.

In an actual aircraft flight environment, passive flow control devices, such as vortex generators, are used to improve the aerodynamic performance of an airfoil. However, it is difficult for these devices to effectively control the flow outside the range of their design specifications. Therefore, active flow control devices attract a lot of interest due to their potential to provide an optimal feedback system for flow control. Especially in unsteady flow, the flow field changes from moment to moment, and therefore, a model to estimate the development of the flow field [5] and an active flow control device to produce the best control effect in each flow field are required. Some existing types of active flow control devices include the plasma synthetic jet actuator [6,7] and the dielectric barrier discharge plasma actuator (DBDPA). A DBDPA generates plasma by applying a voltage to a dielectric between two electrodes, and therefore, it is highly responsive and has a simple structure. Moreover, there is no additional processing of the airfoil model when the DBDPA is installed. For more than a decade, many researchers have been studying an alternating-current-driven DBDPA (ac-DBDPA), which generates plasma by alternating current voltage, and its mechanism and application have been investigated [8–10]. An ac-DBDPA can generate wall jet flow, also called induced flow, and the momentum of the induced flow can be controlled by changing the voltage amplitude and driving frequency. Moreover, unsteady actuation of an ac-DBDPA provides a better control effect than steady actuation [11,12]. Therefore, experiments applying an ac-DBDPA to dynamic stall flow were conducted [13–16]. Post et al. reported on the flow control effect around the NACA0015 airfoil model in dynamic stall flow with a freestream velocity of 10 m/s [13]. However, the ac-DBDPA is known to become less effective as the freestream velocity increases. A nanosecond-pulse-driven DBDPA (ns-DBDPA), which generates plasma by voltage pulses in the order of several hundreds of nanoseconds, has attracted a lot of interest as a device for high freestream velocity flow due to its effectiveness in suppressing flow separation [17–22]. An ns-DBDPA generates a pressure wave and two heated zones when the nanosecond voltage pulse is applied [23]. One heated zone flows downstream along the shear layer, and the other zone flows downstream over the airfoil. These disturbances lead to the formation of vortices. Frankhouser et al. reported the flow control effect around the NACA0015 airfoil model in the dynamic stall flow with a freestream velocity of 67 m/s [24,25]. However, the flow control effect of an ns-DBDPA around a practical airfoil for a helicopter blade and the sensitivity of the ns-DBDPA have not yet been made clear.

In the present study, unsteady pressures were measured in a wind tunnel using an ns-DBDPA as a flow control device. The flow control effect and its sensitivity to pitching oscillation and ns-DBDPA control parameters were investigated. The ns-DBDPA was installed on the leading edge of an airfoil model designed in the form of a helicopter blade. The model was oscillated periodically around 25% of the chord length. Aerodynamic coefficients were calculated from the pressure distribution, which was obtained by unsteady pressure measurements from sensors inside the model.

2. Experiments

2.1. Experimental Apparatus

Wind tunnel tests were conducted at the Japan Aerospace Exploration Agency (JAXA) 2 m × 2 m Low-Speed Wind Tunnel at the JAXA Chofu Aerospace Center. This is a continuous circulation-type wind tunnel and the dimensions of the test section are as follows: a width of 2 m, a height of 2 m, and a length of 4 m. In the test section, the model was oscillated periodically around 25% of the chord length by an oscillating device [15]. Figure 1 shows the oscillating device and the airfoil model installed in the test section.

The flow velocity in the test section was accelerated by the blockage effect. We confirmed that little disturbance exists around the airfoil model in the center of the test section by conducting the wind tunnel experiments without the airfoil model. A two-dimensional airfoil with a 12% airfoil thickness ratio, a 200-mm chord, and a 1000-mm span was used as a test model. The airfoil is designed for use as a helicopter blade. There were four kinds of pressure sensors (Kulite Semiconductor Products, Inc., XCQ-080-0.35BARG and XCQ-0935D; All Sensors Corp., 60INCH-D1-P4V-MINI and 60INCH-D2-P4V-MINI) inside the model. Figure 2 shows the shape of the airfoil model and the position of the sensors inside it.

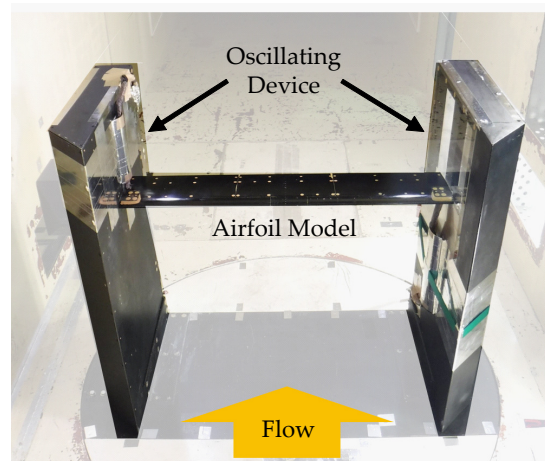


Figure 1. Oscillating device and airfoil model installed in the test section.

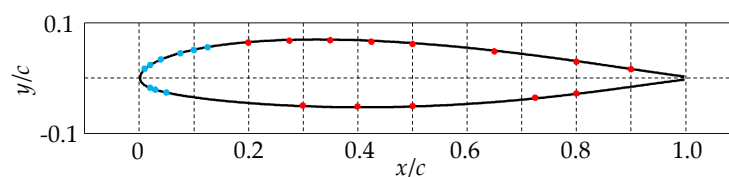


Figure 2. Shape of the airfoil model and position of the sensors, where x and y are the parallel and normal components of the coordinates of the sensor position, respectively, and c is the chord length. Red and blue dots are available and unavailable sensors when the nanosecond-pulse-driven dielectric barrier discharge plasma actuator (ns-DBDPA) is installed, respectively.

The ns-DBDPA covered the sensors installed on the leading edge, and therefore, these sensors were unavailable when the ns-DBDPA was present. Because the airfoil model is made of synthetic wood, the model is insulated from the ns-DBDPA. Different discharge configurations of the ns-DBDPA were adopted. Figure 3a,b show electrode configurations of a double-discharge ns-DBDPA and a single-discharge ns-DBDPA, respectively.

The ns-DBDPA is composed of a copper tape 0.055 mm thick (Lifework Concierge, LCA123), a copper tape 0.08 mm thick (Teraoka Seisakusho, 8323), and a polyimide film 0.07 mm thick (Teraoka Seisakusho, 650S #50), which correspond to an exposed electrode, an insulated electrode, and a dielectric, respectively. Plasma is generated by applying nanosecond voltage pulses to the exposed electrode and the insulated electrode sandwiched between the dielectric. Therefore, the discharge of the generated plasma can be controlled by changing the configuration. The double-discharge ns-DBDPA generates plasma on both the suction and pressure sides, and the single-discharge ns-DBDPA generates plasma on the suction side only. The best control effect is known to be obtained by generating plasma upstream of the separation point [11]. In dynamic stall flow, the separation point is known to change as the angle of attack changes. Therefore, in the double-discharge ns-DBDPA, the plasma was generated at 0% of the chord length on the pressure side. In the single-discharge ns-DBDPA, the position of the ns-DBDPA was moved downstream to investigate the best point for installation of the ns-DBDPA.

We used a custom-designed pulse power source [26] to apply the voltage. Figure 4a,b show the voltage and current waveform of the nanosecond voltage pulse, respectively.

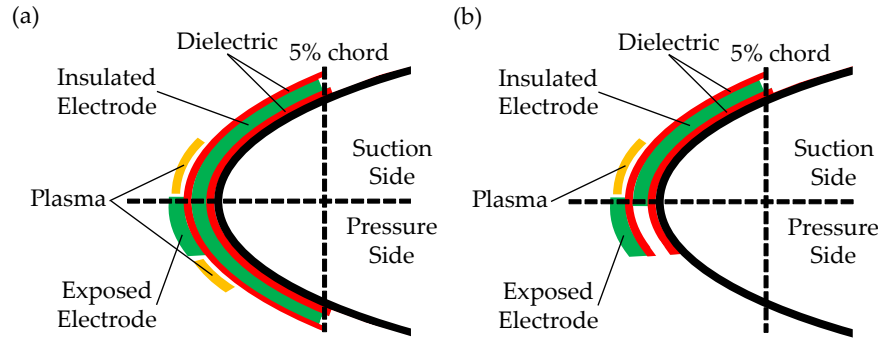


Figure 3. Electrode configurations of (a) double-discharge ns-DBDPA and (a) single-discharge ns-DBDPA.

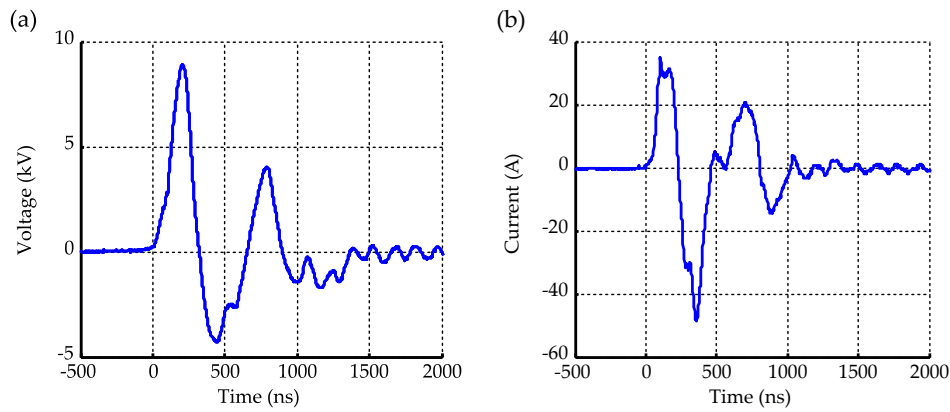


Figure 4. (a) Voltage and (b) current waveforms of the nanosecond voltage pulse.

2.2. Experimental Conditions

Parameters were classified into oscillation and control parameters. The freestream velocity U_∞ (m/s), the mean of the angle of attack α_0 (deg), and the reduced frequency k were chosen as the oscillation parameters. The ranges of these parameters were set to be similar to those in a helicopter flight environment, and the conditions under which a flow control effect was expected to appear were investigated. In these tests, U_∞ was not realized correctly at the model position because of the blockage effect of the oscillating device. The actual velocity was obtained by particle image velocimetry data, and it was found to be from 44 m/s to 61 m/s, corresponding to Reynolds numbers, based on the chord length, from 6.0×10^5 to 8.3×10^5 . The angle of attack α (deg) at a certain time t (s) is calculated with the oscillation frequency f (Hz), α_0 (deg), and the oscillation amplitude β (deg) as follows:

$$\alpha = \alpha_0 + \beta \sin(2\pi ft), \quad (1)$$

and k is calculated with the chord length c (m), U_0 (m/s) and f (Hz) as follows:

$$k = \pi fc / U_0. \quad (2)$$

The nondimensional frequency of the pulse voltage F^+ , the peak pulse voltage V_p , and the type and position of the ns-DBDPA x_{PA}/c were chosen as the control parameters. These parameters were varied over a wide range, and the conditions that maximize the flow control effect were investigated. Here, F^+ is calculated with the frequency of the pulse voltage f^+ (Hz), c (m), and U_0 (m/s) as follows:

$$F^+ = \frac{cf^+}{U_0}. \quad (3)$$

The experimental conditions of the wind tunnel tests are shown in Table 1.

Table 1. Parameter changes for each experimental condition.

Case	U_∞ (m/s)	α_0 (deg)	β (deg)	k	F^+	V_p (kV)	Type	x_{PA}/c (%)
1	50	10	10	0.020π	-	-	-	-
2	50	10	10	0.020π	0.61	8.9	Double	0
3	40–55	10	10	0.020π	0.61	8.9	Double	0
4	50	10–15	10	0.020π	0.61	8.9	Double	0
5	50	10	10	0.004π – 0.032π	0.13–0.96	8.9	Double	0
6	50	10	10	0.020π	0.31–2.5	8.9	Double	0
7	50	10	10	0.032π	0.48–1.9	8.9	Double	0
8	50	10	10	0.032π	0.96	2–8.9	Double	0
9	50	10	10	0.032π	0.48	8.9	Double, single	0
10	50	10	10	0.032π	0.96	8.9	Double, single	0
11	50	10	10	0.032π	0.96	8.9	Single	0–6

Here, the experimental conditions of the wind tunnel test applied to investigate the reliability of the aerodynamic coefficients and the flow control effect are represented by Cases 1 and 2, respectively. The experimental conditions applied to investigate the flow control effect sensitivity are represented by Cases 3 to 11. In Case 5, the frequency of the pulse voltage during a single oscillation is kept constant, and therefore, F^+ increases as k increases. In these tests, β was set 10 deg and the reason is shown in Appendix A.

2.3. Data Processing Method

Unsteady pressure was measured using 23 pressure sensors, as shown in Figure 2. The ns-DBDPA covered the sensors installed on the leading edge, and therefore, aerodynamic coefficients were calculated without the unavailable sensors when the ns-DBDPA was installed. Four kinds of pressure sensors were installed inside the model. High-frequency-response sensors (Kulite Semiconductor Products, Inc., XCQ-080-0.35BARG and XCQ-0935D) and low-frequency-response sensors (All Sensors Corp., 60INCH-D1-P4V-MINI and 60INCH-D2-P4V-MINI) were connected to low-pass filters with steepness values of 135 dB/oct (NF Corp., P-86) and 48 dB/oct (NF Corp., P-85 and 7295), respectively. The cutoff frequency of the low-pass filters is 1000 Hz. The low-pass filters were connected to two kinds of data loggers (Keyence Corp., NR600; National Instruments, cDAQ-9188). The sampling rate and the measurement time were 2000 Hz and 11 s, respectively. The timing of pulses driving the ns-DBDPA was adjusted to the same angle of attack in each oscillation cycle and the data were phase-averaged. Figure 5 shows the timing of pulses driving the ns-DBDPA.

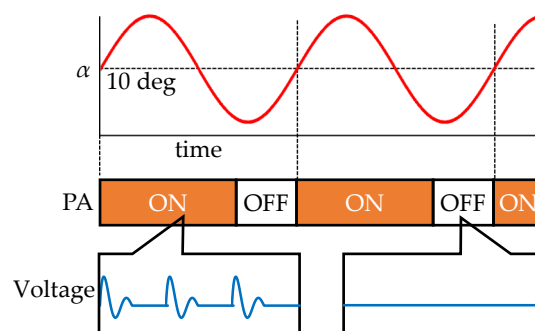


Figure 5. Timing of pulses driving the ns-DBDPA.

The pulses driving the ns-DBDPA were initiated at 10 deg in the pitching-up phase of all cycles. The model was oscillated with f from 1.1 to 8 Hz, and therefore, at least 11 cycles were phase-averaged. The phase-averaged pressure data were used to calculate the pressure coefficient C_p as follows:

$$C_p = -\frac{p - p_\infty}{\rho U_0^2 / 2}, \quad (4)$$

where ρ , p_∞ , and p are the air density, the wind tunnel static pressure, and the phase-averaged pressure, respectively. The aerodynamic coefficients for lift C_l , pressure drag C_{dp} , and pitching moment C_m are calculated by integrating the C_p distribution on the airfoil as follows:

$$C_l = \sum_{i=1}^{i_{\max}-1} \frac{C_{p_i} + C_{p_{i+1}}}{2} \frac{\sqrt{\Delta x^2 + \Delta y^2}}{c} \cos \left(\alpha - \arctan \frac{\Delta y_i}{\Delta x_i} \right), \quad (5)$$

$$C_{dp} = \sum_{i=1}^{i_{\max}-1} \frac{C_{p_i} + C_{p_{i+1}}}{2} \frac{\sqrt{\Delta x^2 + \Delta y^2}}{c} \sin \left(\alpha - \arctan \frac{\Delta y_i}{\Delta x_i} \right), \quad (6)$$

$$C_m = \sum_{i=1}^{i_{\max}-1} \frac{C_{p_i} + C_{p_{i+1}}}{2} \frac{\sqrt{\Delta x_i^2 + \Delta y_i^2}}{c} \left[\left(\frac{x_i + x_{i+1}}{2c} - \frac{1}{4} \right) \cos \left(\arctan \frac{\Delta y_i}{\Delta x_i} \right) + \left(\frac{y_i + y_{i+1}}{2c} \right) \sin \left(\arctan \frac{\Delta y_i}{\Delta x_i} \right) \right], \quad (7)$$

where Δx and Δy are the horizontal and vertical distances between the neighboring sensors, respectively, and $i_{\max}$ is the number of sensors.

3. Results and Discussion

3.1. Reliability of Aerodynamic Coefficients

Some pressure sensors were unavailable when the ns-DBDPA was installed on the airfoil's leading edge. Therefore, aerodynamic coefficients calculated with and without the leading-edge sensors were compared and the reliability of the aerodynamic coefficients was evaluated. Figure 6 shows the C_p distribution of the suction side with and without the leading-edge sensors. The C_p distribution was obtained by linearly interpolating C_p of the neighboring sensors. Figure 7 shows C_l and C_m with and without the leading-edge sensors. The movement of the model is divided into the pitching-up and pitching-down phases. In the pitching-up phase, C_p gradually decreases and C_l linearly increases beyond the static stall angle. Therefore, the flow separation seems to be delayed. At the moment when the model changes from the pitching-up to pitching-down phase, the location where C_p decreases moves from the leading edge to the trailing edge and C_l clearly changes. Therefore, the vortex seems to be generated on the leading edge and convected downstream. In the pitching-down phase until approximately 11 deg, C_p gradually increases and C_l decreases. Therefore, the flow seems to be separated. Suddenly, C_p on the leading edge decreases and C_l increases. Therefore, the flow seems to be attached. Dynamic stall flow is known to cause delayed flow separation beyond the static stall angle, the generation of the dynamic stall vortices, and delayed flow attachment below the static stall angle [4]; therefore, dynamic stall flow was observed in these experiments. Here, the C_p distribution is similar to that in previous experiments [27] conducted with a Reynolds number, based on a chord length of 3.0×10^5 and k of 0.050.

When the leading-edge sensors are blocked, the C_p peak is not observed. However, a decrease in C_p on the suction side at the moment when the model changes from pitching up to pitching down is observed. Therefore, the dynamic stall vortex was resolved. C_l and C_m in both cases are different, and therefore, it is difficult to evaluate the aerodynamic coefficients quantitatively when the suction peak is not resolved. The predominant differences in both cases are the slope of C_l in the pitching-up

phase and the peak of C_l at the moment when the model changes from pitching up to pitching down. In the pitching-down phase, the C_p peak is not observed, and therefore, the influence of the lack of the pressure sensors on the leading edge to qualitative evaluations of C_l and C_m are considered to be small. The trends of C_l in both cases are qualitatively similar, though it should be noted that C_l is underestimated overall and the effect of the vortex is overestimated when the suction peak is not resolved. Similarly, C_m in both cases is qualitatively different compared with C_l . This might be because C_m is more sensitive to the suction peak of the pressure. The evaluation of the value of C_m is difficult because of lack of pressure sensors on the leading edge, and it is just shown as reference data [24]. Therefore, we evaluated the control effect qualitatively using C_l rather than C_m . It is difficult to evaluate the error of C_l and C_m in the present study, and therefore, the flow control effect is evaluated qualitatively. A more quantitative discussion is left for a future study.

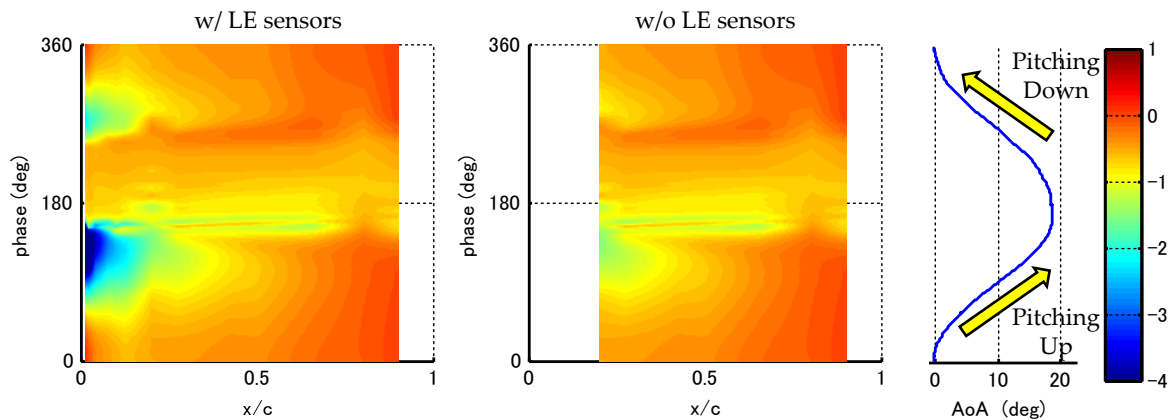


Figure 6. Pressure coefficient distribution of the suction side, which is calculated with and without leading-edge (LE) sensors when the ns-DBDPA is not installed. The experimental conditions are shown in Case 1 in Table 1.

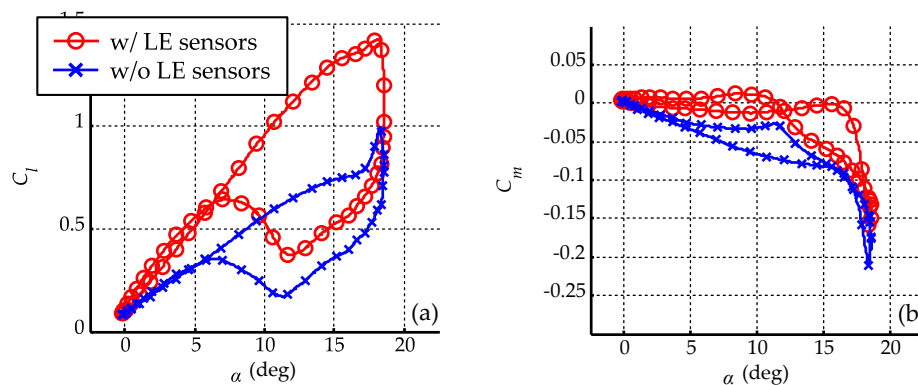


Figure 7. (a) Lift coefficient and (b) pitching moment coefficient calculated with and without leading-edge (LE) sensors when the ns-DBDPA is not installed.

3.2. Flow Control Effect

The aerodynamic coefficients with and without driving the ns-DBDPA are compared, and the flow control effect was investigated. Figure 8 shows the C_p distribution on the suction side in the cases with and without driving the ns-DBDPA. Figure 9a–c show C_l , C_{dp} , and C_m , respectively, in the cases with and without driving the ns-DBDPA. $C_{l,up}$ and $C_{l,down}$ are defined as the lift coefficients in the pitching-up and pitching-down phases, respectively. The C_p distribution in the pitching-up phase and that in the pitching-down phase are different. The difference results in hysteresis of the aerodynamic coefficients. A comparison of the two conditions shows that there is little difference

in the C_p distribution except during the pitching-down phase. In the pitching-down phase, when the ns-DBDPA is driven, locations where C_p decreases appear repeatedly. Therefore, $C_{l,down}$ when the ns-DBDPA is driven is clearly larger than that when the ns-DBDPA is not driven. As a result, the ns-DBDPA can reduce the hysteresis of C_l . Not only the hysteresis of C_l but also the hystereses of C_{dp} and C_m are reduced by driving the ns-DBDPA. The flow control effect is evaluated using the efficiency of the lift enhancement η [15] as follows:

$$\eta = \frac{\oint C_l(\alpha)_{w/oPA} d\alpha - \oint C_l(\alpha)_{w/PA} d\alpha}{\oint C_l(\alpha)_{w/oPA} d\alpha}, \quad (8)$$

where w/ PA and w/o PA are the cases with and without driving the ns-DBDPA, respectively. η increases as the hysteresis decreases when the ns-DBDPA is driven. The lift enhancement effect, which is produced when driving the ns-DBDPA, is accompanied by the fluctuation of these coefficients. The frequency of the fluctuation corresponds to f^+ . This result indicates that the fluctuation is caused by the vortices generated when the ns-DBDPA is driven. Here, vortices are considered to be generated by driving the ns-DBDPA installed on the leading edge of the NACA0015 airfoil model; therefore, a similar phenomenon to that in the previous study [27] seems to be observed in the flow fields around the oscillating airfoil in the present study. In a previous study, Post et al. also reported that the flow separation control is effective in the pitching-down phase because the disturbance at the leading edge brings high momentum flow near the surface [13]. Moreover, the leading-edge vortex is formed and induces the lift. It should be noted that the flow control effect is observed in the pitching-down phase and the influence of the leading-edge sensors to the qualitative evaluation of C_l is small. Therefore, it is possible to discuss the qualitative effect of the control without the leading-edge sensors.

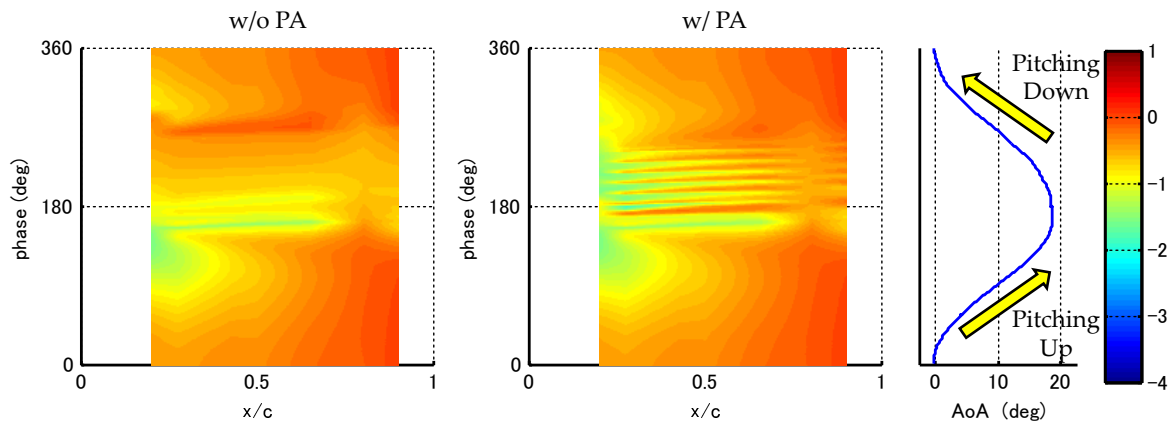


Figure 8. Pressure coefficient distribution of the suction side in the cases with and without driving the ns-DBDPA. The experimental conditions are shown in Case 2 in Table 1.

3.3. Flow Control Effect Sensitivity of Parameters

The different values of aerodynamic coefficients that change the oscillation and control parameters are compared, and the sensitivity of the flow control effect to these parameters is investigated.

3.3.1. Freestream Velocity

Figure 10a,b show C_l under different U_∞ conditions in the cases without and with driving the ns-DBDPA, respectively. When the ns-DBDPA is not driven, $C_{l,up}$ does not change as U_∞ increases. However, $C_{l,down}$ with $U_\infty = 40$ m/s is the smallest of the three cases. The flow control effect appears in all the cases. However, the phase of the fluctuation of $C_{l,down}$ differs. f^+ increases as U_∞ increases while keeping F^+ constant, and therefore, the phase difference is caused by the difference in f^+ . Figure 11 shows the effect of U_∞ on η . There is little difference between η with $U_\infty = 40$ m/s and

$U_\infty = 55$ m/s, so the sensitivity of η to U_∞ is low. The flow control effect of the ns-DBDPA is expected to appear at higher freestream velocities.

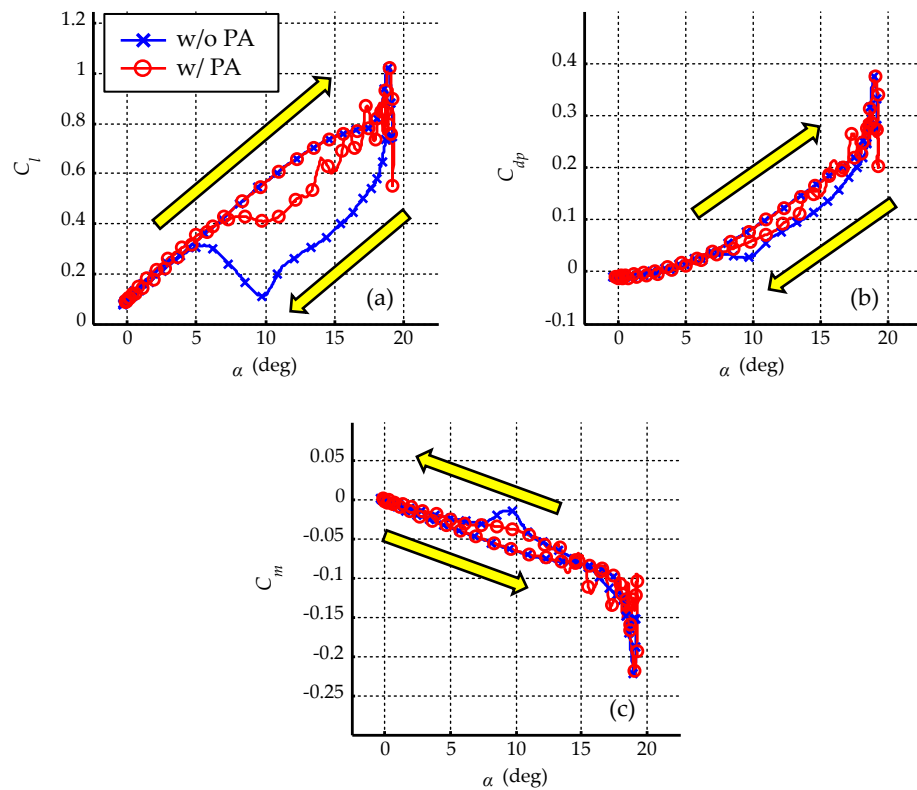


Figure 9. (a) Lift coefficient, (b) pressure drag coefficient, and (c) pitching moment coefficient in the cases with and without driving the ns-DBDPA.

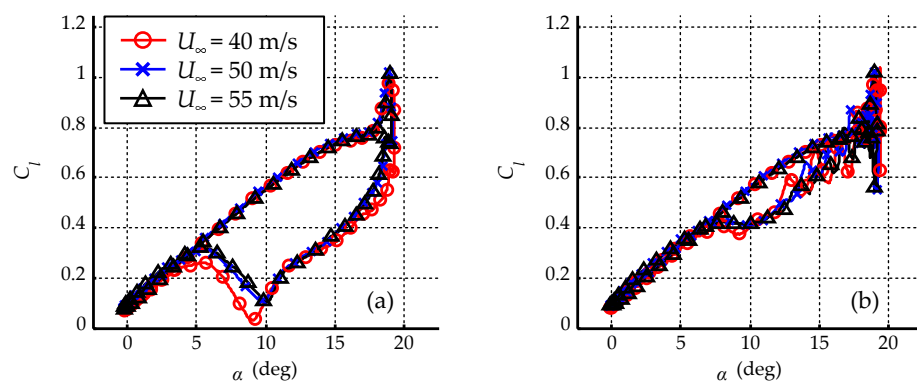


Figure 10. Lift coefficients under different freestream velocity conditions. Here, (a,b) correspond to without and with driving the ns-DBDPA, respectively. The experimental conditions are shown in Case 3 in Table 1.

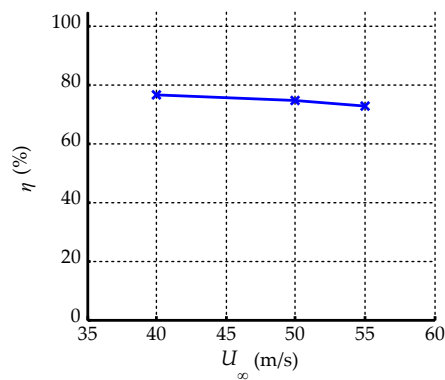


Figure 11. Effect of the freestream velocity on the efficiency of the lift enhancement.

3.3.2. Mean of the Angle of Attack

Figure 12a,b show C_l under different α_0 conditions in the cases without and with driving the ns-DBDPA, respectively. When the ns-DBDPA is not driven, $C_{l,down}$ with $\alpha_0 = 15$ deg is smaller than that with $\alpha_0 = 10$ deg, and therefore, the hysteresis is exacerbated as α_0 increases. When the ns-DBDPA is driven, the hysteresis is also exacerbated as α_0 increases. In both cases with $\alpha_0 = 15$ deg, fluctuations in $C_{l,up}$ are observed. This result indicates that the peaks are caused by the dynamic stall vortices. $C_{l,down}$ clearly increases when the ns-DBDPA is driven, while $C_{l,up}$ does not change. This result indicates that the ns-DBDPA has little effect on the dynamic stall vortex. Figure 13 shows the effect of α_0 on η , which decreases as α_0 increases.

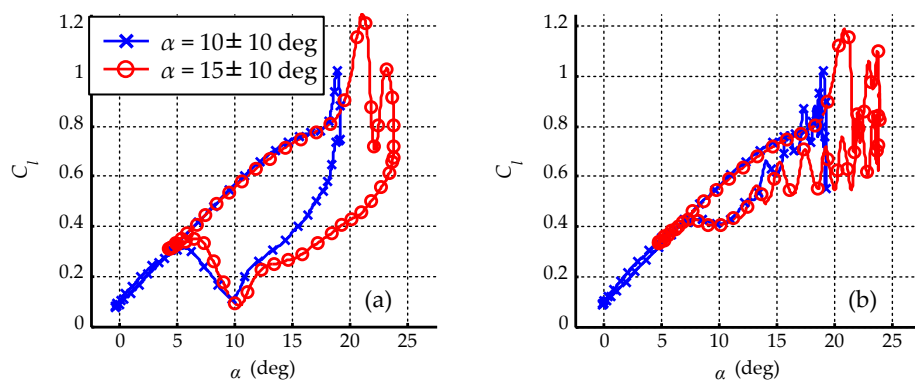


Figure 12. Lift coefficients under different means of the angle of attack. Here, (a,b) correspond to without and with driving the ns-DBDPA, respectively. The experimental conditions are shown in Case 4 in Table 1.

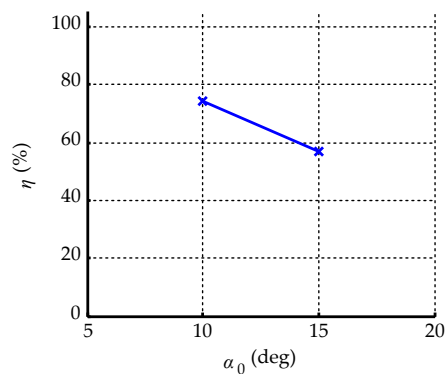


Figure 13. Effect of the mean of the angle of attack on the efficiency of the lift enhancement.

3.3.3. Reduced Frequency

Figure 14a,b show C_l under different k conditions in the cases without and with driving the ns-DBDPA, respectively. When the ns-DBDPA is not driven, the hysteresis is exacerbated as k increases. When the flow around the airfoil is attached, C_l changes linearly. Therefore, the range of α at which the flow is attached decreases as k increases. $C_{l,up}$ with $k = 0.004\pi$ does not increase linearly because the flow is separated. The flow control effect appears in all the cases. Especially, $C_{l,down}$ at $k = 0.004\pi$ dramatically increases when the ns-DBDPA is driven. Figure 15 shows the effect of k on η . The flow control effect appears in all the cases, but η decreases as k increases. η at $k = 0.004\pi$ exceeds 100% because the hysteresis of C_l becomes larger with driving the ns-DBDPA than that without driving ns-DBDPA.

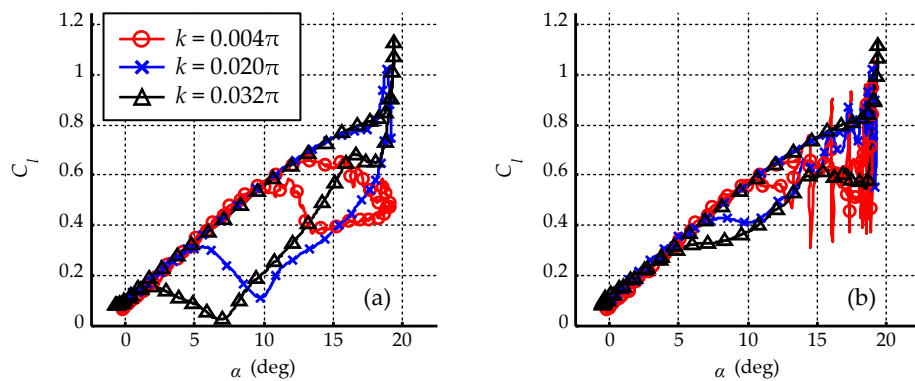


Figure 14. Lift coefficients under different reduced frequency conditions. Here, (a,b) correspond to without and with driving the ns-DBDPA, respectively. The experimental conditions are shown in Case 5 in Table 1.

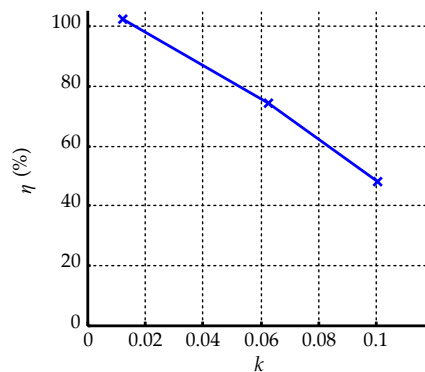


Figure 15. Effect of the reduced frequency on the efficiency of the lift enhancement.

3.3.4. Nondimensional Frequency of Pulse Voltage

Figure 16a,b show C_l under different F^+ conditions when k is 0.020π and 0.032π , respectively. Figure 17 shows the effect of F^+ on η , which increases as F^+ decreases. Thus, a lower F^+ is effective for flow control in the range investigated. However, the flow control effect is estimated to decrease as F^+ further decreases when F^+ is less than 0.5 because the vortices that affects the lift enhancement mechanism does not seem to be formed on the airfoil. Although additional tests over a wider frequency range are required for the investigation of the optimal F^+ , the best flow control effect is obtained with an F^+ of 0.5 in the range we investigated. In both cases, $C_{l,down}$ clearly increases when the ns-DBDPA is driven. Moreover, the amplitude of the fluctuation decreases and the frequency of the fluctuation increases as F^+ increases. This result indicates that C_l is influenced by the vortices generated by the ns-DBDPA. A trade-off relationship exists between η and the amplitude of the C_l fluctuation. Similar

phenomena were observed in the dynamic stall flow around the NACA0012 airfoil, and Singhal et al. reported that the fluctuation was observed at low F^+ numbers [27].

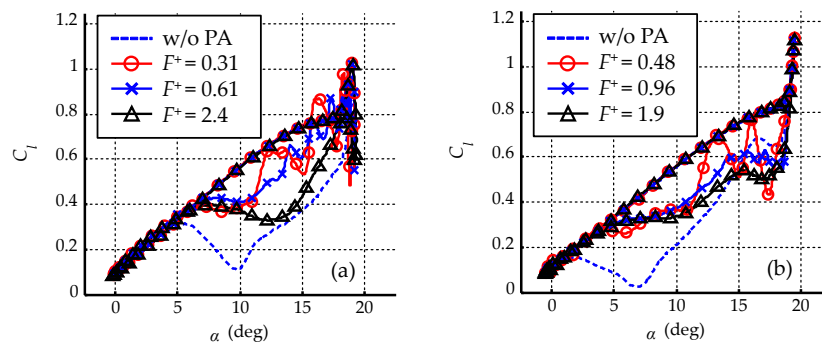


Figure 16. Lift coefficients with different nondimensional frequency of pulse-voltage conditions when the reduced frequency is (a) 0.020π and (b) 0.032π . The experimental conditions are shown in Cases 6 and 7 in Table 1.

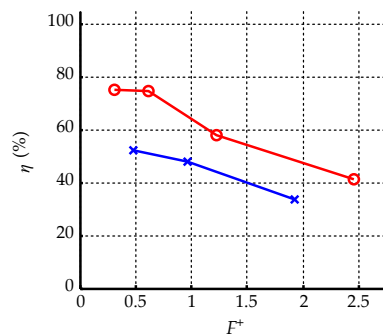


Figure 17. Effect of the nondimensional frequency of the pulse voltage on the efficiency of the lift enhancement.

3.3.5. Peak Pulse Voltage

Figure 18 shows C_l under different V_p conditions. $C_{l,down}$ with $V_p = 2$ kV is smaller than with $V_p = 3$ kV. Figure 19 shows the effect of V_p on η . η does not change as V_p changes when V_p is larger than 2 kV. When a higher V_p is applied, more heat is produced by the generation of plasma. This result indicates that the flow control effect does not change very much, provided that a sufficient amount of heat is input and vortices are generated. A V_p of 3 kV is efficient, considering the flow control effect and the power consumption.

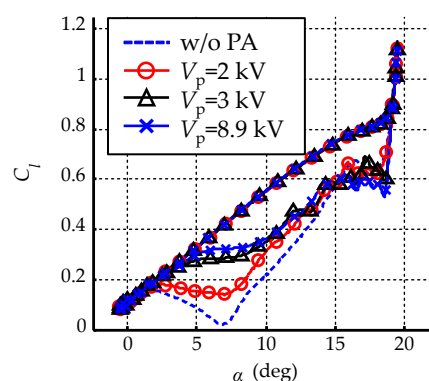


Figure 18. Lift coefficients under different peak pulse-voltage conditions. The experimental conditions are shown in Case 8 in Table 1.

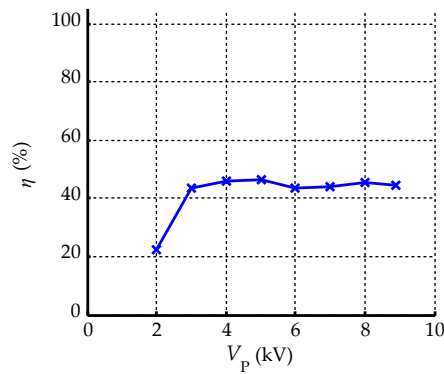


Figure 19. Effect of the peak pulse voltage on the efficiency of the lift enhancement.

3.3.6. Type of ns-DBDPA

Figure 20a,b show C_l with different types of ns-DBDPA when F^+ is 0.48 and 0.96, respectively. When the ns-DBDPA is not driven, $C_{l,up}$ does not differ between the ns-DBDPA types, but $C_{l,down}$ in the single-discharge ns-DBDPA is larger than in the double-discharge ns-DBDPA. The shape of the leading edge differs between the two types, as shown in Figure 3, and therefore, the shape influences the separated flow at a high angle of attack. Similarly, $C_{l,down}$ in the single-discharge ns-DBDPA is also larger than that in the double-discharge ns-DBDPA when the ns-DBDPA is driven. Therefore, the single-discharge ns-DBDPA shows a higher flow control effect regardless of whether the ns-DBDPA is driven. The ns-DBDPA also acts as a passive flow control device under these conditions. Figure 21 shows the effect of the ns-DBDPA types on η . η in the single-discharge ns-DBDPA is larger than that in the double-discharge ns-DBDPA. In summary, a high flow control effect is obtained in the single-discharge ns-DBDPA, and this is caused by not only the difference in the disturbance added by the ns-DBDPA but also the different shapes of the ns-DBDPA types.

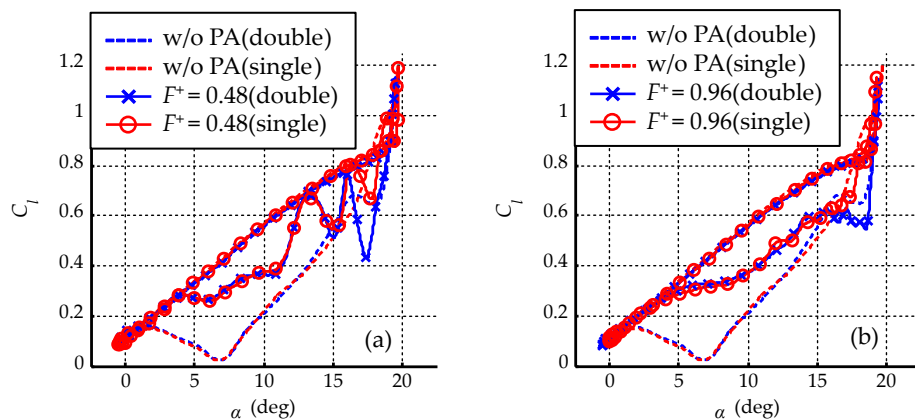


Figure 20. Lift coefficients with different types of ns-DBDPA when the nondimensional frequency of the pulse voltage is (a) 0.48 and (b) 0.96. The experimental conditions are shown in Cases 9 and 10 in Table 1.

3.3.7. Position of ns-DBDPA

Figure 22a,b show C_l under different x_{PA}/c conditions in the cases without and with driving the ns-DBDPA, respectively. $C_{l,down}$ and the peak of C_l at the moment when the model changes from pitching up to pitching down changes as x_{PA}/c changes when the ns-DBDPA is not driven. The shape of the leading edge changes as x_{PA}/c changes, and therefore, the shape difference influences the separated flow and the dynamic stall vortex. The result also shows that the ns-DBDPA also acts as a passive flow control device. When the ns-DBDPA is driven, $C_{l,down}$ changes as x_{PA}/c changes.

The flow control effect is also sensitive to the shape of the leading edge. Figure 23 shows the effect of x_{PA}/c on η . When x_{PA}/c is 0%, η is the highest among the three cases; therefore, an x_{PA}/c of 0% seems to be the most effective.

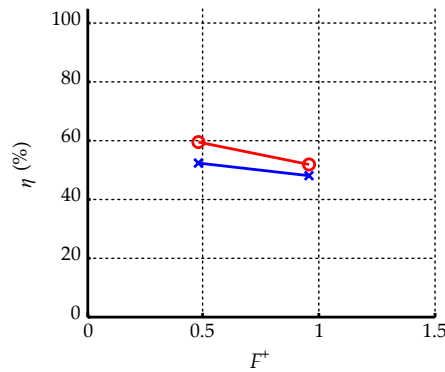


Figure 21. Effect of the ns-DBDPA type on the efficiency of the lift enhancement.

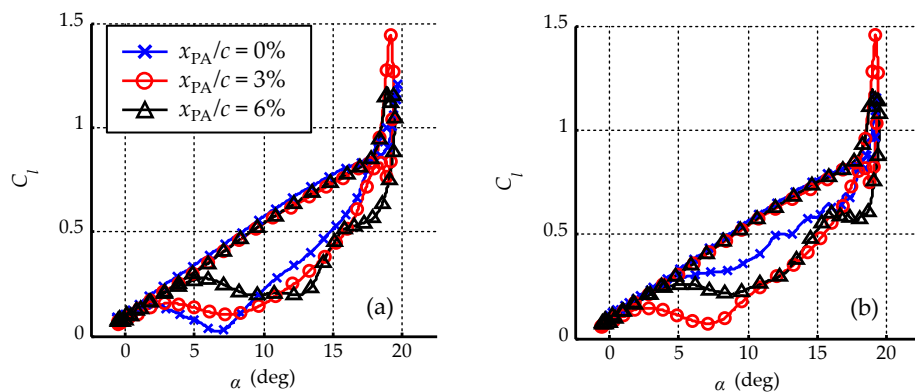


Figure 22. Lift coefficient under different ns-DBDPA positions. Here, (a,b) correspond to without and with driving the ns-DBDPA, respectively. The experimental conditions are shown in Case 11 in Table 1.

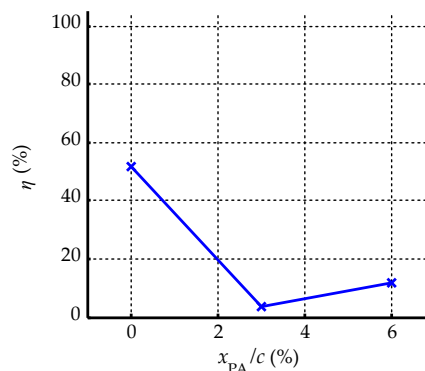


Figure 23. Effect of the position of the ns-DBDPA on the efficiency of the lift enhancement.

4. Conclusions

In the present study, unsteady pressure was measured in a wind tunnel using the ns-DBDPA as a flow control device. The flow control effect and its sensitivity to the pitching oscillation and ns-DBDPA control parameters were investigated. The freestream velocity, the mean of the angle of attack, and

the reduced frequency were employed as the oscillation parameters. Moreover, the nondimensional frequency of the pulse voltage, the peak pulse voltage, and the type and position of the ns-DBDPA were adopted as the control parameters. The ns-DBDPA was installed on the leading edge of an airfoil model that was in the form of a helicopter blade. The model was oscillated periodically around 25% of the chord length. Aerodynamic coefficients were calculated by integrating the pressure distribution that was measured by pressure sensors inside the model. The aerodynamic coefficients are discussed qualitatively because the suction peak was not resolved. Overall, the lift coefficient was underestimated and the effect of the vortex was overestimated.

The results related to the flow control effect are summarized below:

- The lift coefficient increases by driving the ns-DBDPA when the model is pitching down;
- The aerodynamic coefficients corresponding to the frequency of the pulse voltage fluctuate when the ns-DBDPA is applied.

The effects of the model oscillation parameters on the flow control effect are summarized below:

- The flow control effect appears under all conditions in which the freestream velocity, the angle of attack, and the reduced frequency were set to be from 40 m/s to 55 m/s, from 10 ± 10 deg to 15 ± 10 deg, and from 0.004π to 0.032π , respectively;
- Changes in the freestream velocity have little effect on the flow control effect in the range we investigated;
- The flow control effect increases as the mean of the angle of attack and the reduced frequency decrease.

The effects of the ns-DBDPA control parameters on the flow control effect are summarized below:

- The flow control effect increases as the nondimensional frequency of the pulse voltage decreases in the range we investigated, but the amplitude of the lift coefficient fluctuation increases;
- A sufficient flow control effect is obtained when the peak pulse voltage is greater than or equal to 3 kV;
- The flow control effect is sensitive to the shape of the leading edge. The best flow control effect is obtained when the position of the ns-DBDPA is 0% in the single-discharge type in the range we investigated.

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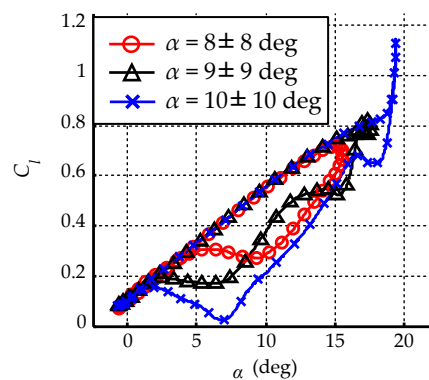
Appendix A. Selection of Oscillating Amplitude

We conducted the experiment to select the oscillating amplitude where the dynamic stall appears. The experimental conditions of the wind tunnel tests are shown in Table A1.

Table A1. The experimental conditions changing the oscillating amplitude.

U_∞ (m/s)	α_0 (deg)	β (deg)	k
50	8–10	8–10	0.032π

Figure A1 shows C_l under different β conditions when the ns-DBDPA is not driven. The peak of C_l decreases as the maximum angle of attack decreases. Therefore, the influence of the dynamic stall vortex decreases as the maximum angle of attack decreases. In the experiments, the oscillation amplitude was set 10 deg.

**Figure A1.** Lift coefficients under different oscillation amplitude conditions when the ns-DBDPA is not driven. The experimental conditions are shown in Table A1.

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