Experimental Parametric Study on Flow Separation Control Mechanisms around NACA0015 Airfoil Using a Plasma Actuator with Burst Actuation over Reynolds Numbers of $10^5$–$10^6$

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Abstract: Dielectric barrier discharge plasma actuators (DBD-PAs) have the potential to improve the performance of fluid machineries such as aircrafts and wind turbines by preventing flow separation. In this study, to identify the multiple flow control mechanisms in high Reynolds number flow, parametric experiments for an actuation parameter $F^+ \text{ with a wide range of } Re$ values ($10^5$–$10^6$) for NACA0015 airfoil was conducted. We conducted wind tunnel tests by applying a DBD-PA to the flow field around a wing model at the leading edge. Lift characteristics, turbulent kinetic energy in the flow field, shear layer height, and the separation point of the boundary layer were evaluated based on pressure distributions on the wing surface and velocity of the flow field, with the effect of DBD-PA on the post-stall flow around the wing and the mechanism behind the increase in the lift coefficient $C_L$ analyzed based on these evaluation results. The following phenomena contributed to the increase in $C_L$: (1) increase in turbulent kinetic energy; (2) increase in circulation; and (3) acceleration of the flow near the leading edge. Thus, this study effectively investigated the dependence of the increase in lift on $F^+$ and the lift-increasing mechanism for a wide range of $Re$ values.

Keywords: active flow control; stall prevention; boundary layer; plasma actuation; dielectric barrier discharge; wind turbine

1. Introduction

In recent years, techniques for preventing boundary layer separation [1] and reducing frictional drag [2] on wings have attracted considerable attention because of the increasing interest in resource efficiency resulting from climate-related issues and the rapid depletion of energy resources. These techniques need to improve the system efficiency of fluid machinery and reduce failures to extend their life. Conventional devices such as flaps and vortex generators are commonly applied to wings. However, the former is often a large and complex mechanical system with high energy consumption; therefore, it can only be applied to a limited variety of wings because of the high manufacturing costs and large size. The latter suffers from a constant increase in drag caused by passively enhanced turbulence. Recently, dielectric barrier discharge plasma actuators (DBD-PAs) were proposed as an alternative to the devices used for fluid control [3–7]. Figure 1 shows our DBD-PA electrode. Among the various active flow control technologies, DBD-PAs can be employed for practical use because they do not have any moving elements and can
induce the relatively large momentum of airflow required for flow control [8–11]. In addition, these devices are lightweight, compact, highly responsive, and easy to install.

Figure 1. DBD-PA electrode before installation on a wing.

Thus far, authors have attempted to apply DBD-PAs to the flow field around wind turbine blades, and they have recognized the importance of mitigating fluctuating load on the blade to improve the efficiency and durability of large wind turbines. An unbalanced load on the rotor can cause serious damage to turbines with rotor diameters exceeding 100 m. Such loads can be caused by nonuniform velocities in the cross-section of the inflow generated by wind shear, the wake of other turbines, and turbulence [12,13]. This problem becomes more apparent in modern designs in which the blade is designed to be longer and slender to accommodate the larger area and lower angular velocity of the rotor [14]. Velocity nonuniformity occurs randomly in the rotor area; therefore, it is difficult to avoid its effect on the flow around the blade by optimizing only the blade shape. Therefore, active flow control is required for developing highly efficient large turbines [15–20].

The power generation efficiency and load of most wind turbines are determined by the lift and lift/drag ratio, similar to aircraft. Velocity nonuniformity on the rotor plane causes the blades to fluctuate in the angle of attack (AoA), and stalls on the blades often occur on turbines which have been installed in locations with high turbulence wind. By preventing this stall with a DBD-PA, it is possible to stabilize the high lift generated on the blades; therefore, the power output from wind energy that could not be captured is recovered to suppress the fluctuating load. This is our concept of improving wind turbine performance using a DBD-PA. In our previous study, we investigated the power improvement effect by a smart rotor with a DBD-PA mounted on the blades of a 300 kW wind turbine in a test field [21,22]. The Reynolds number of the flow around the blades of this turbine rotor ranged between $1.0 \times 10^6$ and $3.0 \times 10^6$. Additionally, the fluctuating load reduction on the blades in another wind turbine with a DBD-PA was investigated, whereas the Reynolds number of the flow around the blades was $5.0 \times 10^5$ [23]. In these previous field tests, we improved the aerodynamic performance of a turbine and reduced the fluctuating load on the blades through plasma actuation under limited conditions; however, the mechanism of these improvement could not be clarified as the effects of the device on the flow field around the airfoils at each wing section at high Reynolds numbers (Re) remain unclear.

Previous studies on 2D wing models in a flow with a low Re number ($10^4$–$10^5$) demonstrated that flow separation around an airfoil at a post-stall angle of attack (AoA) was suppressed significantly. The results confirmed that the stall angle was delayed and the lift increased [24–34]. In this Re number range, certain high-resolution numerical analyses validated by experiments demonstrated the detailed mechanism of flow control [35–37]. Therefore, the performance of wind turbines using a DBD-PA can be improved by reducing the effect of stalls on the wind turbine blade caused by fluctuation in the AoA attributed to the velocity nonuniformity in a low Re number flow field, e.g., a flow field around a small wind turbine under fluctuating natural wind conditions [38].
Thus far, 2D wing models have been extensively investigated via numerical analyses to understand the effects of DBD-PA at a high $Re$ number of $\sim 10^6$ [39,40]. The results showed that the characteristics of the boundary layer separation and shear layer on the suction side flow of the wing were strongly affected by DBD-PA actuation downstream of the leading edge. DBD-PA actuation caused a laminar–turbulence transition of the boundary layer under certain flow conditions and generated a large vortex in the shear layer under other flow conditions. Furthermore, these results indicate the need for a suitable control criterion for DBD-PA actuation based on the flow conditions.

Suzen and Huzn’g’s simplified equation model [41] is used for simulating the plasma effect in the numerical analysis of the flow control effect of a DBD-PA on the flow around a wing. This model is quasi-steady, does not consider plasma generation, and depends on Poisson’s equation for the electric field vector and charge distribution. Therefore, the plasma effect on flow control does not include the effects of spatially distributed streamers or heat generation. Thus, it is difficult to quantitatively match the input energy to obtain the same fluid control effect as in the comparative experimental results. Furthermore, the results of the numerical analyses conducted in previous studies could be influenced by numerical boundary conditions because of the insufficient wingspan. Therefore, new experimental research is indispensable to clarify the flow control mechanism of plasma actuation and the actual effect of fluid control that can be obtained at a high $Re$ number.

A few experimental results under such high $Re$ conditions exist [42–49]; however, they cannot sufficiently validate the fundamental investigations discussed earlier. Thus, although the flow control effect and mechanisms of the DBD-PA actuation for flow fields under high $Re$ numbers have been suggested based on the results of numerical investigations, these suggestions need to be validated based on the phenomena observed in the experimental studies.

Many electrical operating parameters are used to control the flow in a DBD-PA because it directly generates body force from the electric field. “Burst frequency” is the most well-known among these operating parameters. The effect of DBD-PA on stall suppression can be enhanced by modulating the base-applied AC voltage at a predetermined burst frequency compared to that using continuous AC actuation [42,50–56]. This phenomenon depends on the dimensionless frequency, $F^+$, expressed as [35–41,50]:

$$
F^+ = \frac{f c}{u_{\infty}}
$$

where $c$, $u_{\infty}$, and $f$ represent the chord length, freestream velocity, and burst frequency, respectively.

Previous studies showed that the effectiveness of DBD-PA in improving lift is strongly affected by $F^+$. For example, some studies reported that the most effective $F^+$ is unity [42,50], whereas others reported that a higher control effect can be obtained at a higher frequency [51]. Several numerical studies have been conducted on this topic. For example, Sato et al. [40] showed that DBD-PA is effective at $\sim 1$ under a high $Re$ number flow. However, for a low $Re$ number flow, Sato et al. [39,57], Asada et al. [58,59], Aono et al. [60], and Fuji [61] reported results with more effective burst frequencies, where $F^+$ ranged between 4 and 10 instead of 1. Based on these previous studies, the authors consider the following reasons why the optimum $F^+$ differs depending on each study: there are multiple mechanisms by which DBD-PA controls the flow field, and which of these mechanisms contributes depends on the several dominant flow field parameters. These parameters include, for example, the boundary layer condition (turbulent/laminar) near the DBD-PA electrode and the position of the boundary layer separation.

In this study, in order to clarify whether this conjecture is correct, parametric experiments were conducted for $F^+$ with a wide range of $Re$ values ($10^4$–$10^6$) in various flow fields that can be caused by a wide range of $Re$ conditions. Additionally, the flow fields controlled by DBD-PA actuation in the post-stall flow field were visualized to
quantify the flow field parameters. By conducting these experiments, we aimed to identify the multiple flow control mechanisms that exist within the experimental condition. The experimental conditions were set such that the results could be compared with those of previous studies that considered low Re and used numerical analyses for high Re. Subsequently, the flow control effect and mechanisms were investigated experimentally for a one-wing model using a wind tunnel under the same inflow quality to fix all flow conditions that affected the effective $F^+$ except $Re$, such as the test facility and airfoil. The dependence of the increase in lift on $F^+$ and the lift-increasing mechanism for a wide range of $Re$ values were investigated by focusing on the effect of DBD-PA actuation in the post-stall flow field.

2. Experimental Method

2.1. Wind Tunnel Facility and Wing Model

Wind tunnel testing was performed in a closed-circuit wind tunnel at the National Institute of Advanced Industrial Science and Technology in Japan. Figure 2 shows a schematic of the wind tunnel facility, coordinate axes, and a photograph of the wing model used in this experiment. This wind tunnel has a test section with a 1.4 × 1.4 m² square cross-section. Furthermore, a two-dimensional NACA0015 wing model with a chord length of 0.3 m as shown in Figure 3 was used. The span length of the model, i.e., the model length in the z-direction, was 1.4 m. The aspect ratio and maximum blockage ratio of the airfoil model were 0.21 and 0.11, respectively. In this airfoil, the boundary layer near the leading edge transitioned from laminar to turbulent in the $Re$ conditions in this study ($10^3$–$10^6$), and the position of the boundary layer separation and the stall angles changed gradually in this range of $Re$ values. These stall characteristics resulted in various post-stall flow fields depending on the $Re$ values. This airfoil is not commonly used for commercial wind turbine blades; however, it is appropriate for observing various flow fields in the experiments. Therefore, this airfoil was selected to investigate the flow control mechanism based on the assumption that the flow control effect depends on the flow field conditions rather than on the type of airfoil. The reference flow velocities in this experiment were 10, 22, 30, and 50 m/s, and the corresponding $Re$ numbers were $1.9 \times 10^5$, $4.2 \times 10^5$, $5.7 \times 10^5$, and $9.4 \times 10^5$, respectively. The turbulence intensity of the freestream in the measurement section at velocities exceeding 10 m/s was less than 0.5%. The surface pressure on the wing model was measured using 36 pressure ports: 24 on the suction side and 14 on the pressure side, as illustrated in Figure 3. Table 1 lists the locations of the wall-pressure ports. The positions of all ports in the z-direction (i.e., the spanwise direction of the wing) were carefully designed to eliminate the effect of turbulence from the upstream ports. The ports positioned downstream were arranged further away from the center of the wind tunnel height ($z = 0$) in the positive z-direction on the suction side surface and in the negative z-direction on the pressure side surface. An AoA condition, which was the angle between the chord line and the mainstream, as shown in Figure 4, was in the range of $0°$ to $30°$. The model was intermittently rotated around the z-axis to increase or decrease the AoA within the range quasi-statically; this motion is called the pitch sweep. The motion for increasing the AoA is called pitch-up and the motion for decreasing is called pitch-down. In this experiment, the distribution of the time-averaged surface pressure for each AoA was measured. The distributions of the pressure coefficient, $C_p$, along the chord direction and lift coefficient, $C_L$, for each AoA were calculated from the surface pressure. At $24°$, the velocity field around the suction side of the wing model was observed using particle image velocimetry, and the flow pattern was subsequently investigated. One thousand pairs of particle images were acquired at repetition frequencies of up to 15 Hz. The time-averaged velocity fields were calculated from these images using a fast-Fourier-transform-based cross-correlation method. Under all conditions, the repetition frequency of the laser light was set out of synchronization with the burst frequency of the DBD-PA determined using $F^+$ and the reference flow velocity. Particles composed of dioctyl...
sebacate were generated using Raskin nozzles. The gaps between the wing model and both sidewalls of the wind tunnel were as small as possible, and no side fences were used. Therefore, the pressure and velocity fields were measured near the center of the wing model in the span direction to avoid interference from the boundary layer on the sidewall.

**Figure 2.** Schematic of the wind tunnel facility (left) and actual photograph of the wing model (right).

**Figure 3.** Schematic of the airfoil shape and pressure port locations.
Figure 4. Schematic of the DBD-PA installed on the leading edge of the wing model and power supply system.

Table 1. Position of pressure ports on the wing model.

<table>
<thead>
<tr>
<th>Suction Side</th>
<th>Pressure Side</th>
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<td>x/c</td>
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<tr>
<td>* −0.3</td>
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<tr>
<td>* −0.29</td>
<td>0.009</td>
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<tr>
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<tr>
<td>−0.26</td>
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<tr>
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<tr>
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<tr>
<td>−0.18</td>
<td>0.055</td>
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<tr>
<td>−0.14</td>
<td>0.064</td>
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<tr>
<td>−0.1</td>
<td>0.073</td>
</tr>
<tr>
<td>−0.053</td>
<td>0.082</td>
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<tr>
<td>0</td>
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<tr>
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<tr>
<td>0.6</td>
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* The pressure in those ports was not measured because these were covered by the DBD-PA electrode.
2.2. DBD-PA System

Figure 4 shows a schematic of the DBD-PA system, which consisted of a DBD-PA electrode and a power supply unit. For the DBD-PA electrode (Asahi Rubber Co., Ltd.), a silicone rubber dielectric (thickness = 0.4 mm) was sandwiched between a pair of titanium-film electrodes (thickness = 0.05 mm), i.e., a high-voltage electrode and grounded electrode. A high-voltage electrode was set on the pressure side of the wing model, and its upstream edge was along the leading edge. A grounded electrode was implanted into the dielectric and placed on the suction side. The dielectric was flush-mounted on the surface of the wing, and a high-voltage electrode was attached to the dielectric surface like a trip wire. The widths of the former and latter electrodes were 6 and 10 mm, respectively, and the electrodes overlapped by ~1 mm. In this configuration, the plasma-induced flow blew from the leading edge toward the suction side of the wing model.

The power supply system consisted of a DC power unit, an AC inverter, and a high-voltage transformer. The output of the DC power unit was converted into a high-frequency AC waveform by the AC inverter, which was subsequently boosted by the transformer. The transformer output was connected to each titanium-film electrode. The amplitude of the applied voltage was 9 kV_{pp} with a base frequency of 99 kHz. In addition, the applied voltage was modulated using a normalized burst frequency, F^+, as illustrated in Figure 5. The values of F^+ in these experimental conditions were 0.1, 0.5, 1, 5, 10, 50, and 100. The function generator provided a control signal to determine the burst frequency and duty ratio of the inverter. The duty ratio is defined as a fraction of the duration of plasma activation in one period of the modulation waveform. This value was fixed at 34% throughout the experiments. The time-averaged input power was the same under all conditions because the input power was determined using the base frequency, the voltage applied to the electrodes, and the duty ratio. The waveform applied to the electrode was monitored using an oscilloscope, a high-voltage probe, and a current transformer; it was adjusted to the experimental conditions by controlling the output voltage of the DC power unit and signal of the function generator.

![Figure 5. Voltage waveform and parameters for DBD-PA actuation.](image-url)
3. Experimental Results and Discussion

3.1. Flow Characteristics without DBD-PA Actuation Classified by $C_L$ and $C_p$ Distributions

Figure 6 shows the $C_L$ curves without DBD-PA actuation, indicating the difference between the curve shapes of each $Re$ number condition. Each $C_L$ curve was calculated by integrating the time-averaged pressure distribution of the wing surface along the chord. Among the pressure distributions without DBD-PA actuation used in the integration, the results for the angles of attack of $13^\circ$, $15^\circ$, $18^\circ$, and $24^\circ$ in the pitch-up runs are shown in Figure 7. The integral for calculating each $C_L$ was performed downstream from the 8.7% chord for all conditions because of the following reasons: (i) the DBD-PA electrode was covered by pressure ports at the leading edge of the wing model; and (ii) when $Re = 9.4 \times 10^5$, the pressure at the 0–6.0% chord position exceeded the measurable limit of the pressure sensor.

Figure 6. $C_L$ curves without DBD-PA actuation.

Figure 7. $C_p$ distribution on the wing model surface without DBD-PA actuation on each $Re$ number and AoA.

The $C_L$ curves of the pitch-up run in Figure 6 exhibit peaks around a $13^\circ$ AoA; simultaneously, the negative $C_p$ near the leading edge shows a large peak during an increase in $C_L$ with angles of attack of 1–13°, as shown by the black curves in Figure 7 for $13^\circ$. Considering the pressure distribution on the suction surface of the airfoil, this observation is attributed to the flow attached to the wing model and the negative $C_p$ that increases based on Bernoulli’s theorem for accelerated flow. Downstream of the leading
edge, the fully attached flow recovers pressure with deceleration toward the trailing edge, and the pressure at the trailing edge approaches the surrounding pressure. Therefore, $C_p$ approaches zero for a 13° AoA.

The $C_L$ values for the region around angles of attack of 14–17° at $Re = 4.2 \times 10^5$, 5.7 $\times 10^5$, and 9.4 $\times 10^5$ decrease gradually. $C_p$ does not recover as much at the trailing edge, and a flat $C_p$ distribution is observed near the 40–50% chord location to the trailing edge for a 15° AoA under the Reynolds numbers, as shown by the blue curves in Figure 7. These results suggest a partial separation on the latter half of the airfoil at angles of attack of 14–17°. For $Re = 9.4 \times 10^5$, the aforementioned range is extended to larger angles. At each angle in this range, a negative $C_p$ peak is observed around the leading edge. The foot of the peak narrows, and the starting position of the flat $C_p$ distribution moves toward the leading edge with an increase in the AoA. This phenomenon suggests that complete leading edge separation of the boundary layer does not occur up to 24° under this $Re$ condition, and the separation point of the boundary layer moves up to the leading edge with an increase in the AoA.

A considerable difference in the pressure distribution exists between 14° and 17° angles of attack and at greater angles under $Re = 1.9 \times 10^5$, 4.2 $\times 10^5$, and 5.7 $\times 10^5$. As indicated by the red curves in Figure 7, a negative $C_p$ peak on the suction side is not observed at higher angles, which results in a flat $C_p$ distribution. No pressure recovery occurs at the trailing edge, and a larger negative $C_p$ is observed because a low-velocity area with almost no acceleration or deceleration is formed on the entire surface of the suction side because of the boundary layer separation at the leading edge. Considering the drastic change in $C_L$ in the range of the AoA shown in Figure 6, the separation point of the boundary layer appears to move discontinuously to the leading edge at a 15° AoA for $Re = 1.9 \times 10^5$ and 18° for $Re = 4.2 \times 10^5–5.7 \times 10^5$. These descriptions in such AoA and $Re$ conditions are consistent with the condition for determining a stall, in which the flow separates from the wing surface and the wing loses a significant amount of $C_L$.

Strong hysteresis is also observed between the pitch-up and pitch-down motions around angles of attack of 13–18° for $Re = 1.9 \times 10^5–5.7 \times 10^5$ (Figure 6). The hysteresis observed in the $C_L$ curve is attributed to the bursting and reformation of a small laminar separation bubble near the leading edge of the wing, which depends on changes in the AoA. The position of the laminar separation bubble suggested by the shape of the $C_p$ distribution is indicated by the red arrow in Figure 7 for $Re = 1.9 \times 10^5–5.7 \times 10^5$. The boundary layer separation occurs in the laminar state after the bursting of the laminar separation bubble in the aforementioned range of $Re$. In contrast, there is no hysteresis in the $C_L$ curve for $Re = 9.4 \times 10^5$. These results suggest that the laminar separation bubble is very small or is not formed, and a turbulent transition of the boundary layer occurs further upstream around the leading edge than that under the other $Re$ conditions. The separation points of the boundary layer determined from the particle image velocimetry (PIV) results are 0.07c, 0.065c, 0.065c, and 0.2c for $Re = 1.9 \times 10^5$, 4.2 $\times 10^5$, 5.7 $\times 10^5$, and 9.4 $\times 10^5$, respectively. This result also supports the consideration that the turbulent transition occurred closer to the leading edge at $Re = 9.4 \times 10^5$ than that at the other $Re$ values.

According to the above description, the flow can be characterized into three different patterns: (1) the boundary layer completely attached on the suction side; (2) the boundary layer partially separated along the chord length; and (3) the boundary layer completely separated at the leading edge. In the first flow pattern, a negative $C_p$ peak formed at the leading edge, and $C_p$ recovered toward the trailing edge. The $C_p$ distribution showing this flow pattern is indicated by the black lines in Figure 7a–d. In the second flow pattern, a negative $C_p$ peak exists at the leading edge, $C_p$ recovery occurs up to the middle chord of the wing model, and a flat distribution of $C_p$ appears near the trailing edge. The $C_p$ distributions corresponding to the second flow pattern are indicated by blue lines. In the third flow pattern, no negative $C_p$ peak is observed, and the $C_p$ distribution is flat over the
suction side of the wing model. $C_p$ distributions corresponding to the last characteristic are indicated by red lines.

3.2. Dependence of the Increase in $C_L$ by DBD-PA Actuation on Flow Characteristics

Figure 8a–d shows the dependence of $C_L$ on the AoA at each Reynolds number without (as shown in “w/o DBD-PA”) and with DBD-PA actuation, with $F^+ = 0.1, 1, 10,$ and $100$. Each $C_L$ value was calculated using the $C_p$ distributions obtained under identical flow and plasma conditions. For example, each plot of the “w/o PA” condition at $\alpha = 13^\circ$, $15^\circ$, $18^\circ$, and $24^\circ$ was calculated from the corresponding $C_p$ distribution shown in Figure 7. Considering all $C_p$ distributions under conditions without plasma actuation obtained in this experiment, including the examples shown in Figure 7, the ranges of the angles of attack in the top figures are colored gray, blue, and red for the first, second, and third flow patterns described in Section 3.1, respectively.

Figure 8e–h shows the increase in $C_L$ caused by the DBD-PA actuation with respect to $F^+$ and the AoA. The value of $C_L$ increased, and $\Delta C_L$ was calculated using the following equation:

$$\Delta C_L = C_L - C_{L,NoPA}$$

In Figure 8e–h, there is a negligible increase or decrease in $C_L$ regardless of the $Re$ number, in the range of angles of attack corresponding to the gray range shown in Figure 8a–d. In the range of angles of attack corresponding to the blue range, $C_L$ is only slightly affected. For $Re = 4.2 \times 10^5$ (Figure 8b,f), the increase in $C_L$ is negative at a high $F^+$. For $Re = 5.7 \times 10^5$ (Figure 8c,g), the increase in $C_L$ is slightly positive. Some peaks of $C_L$ increase were observed for every $Re$ number condition. At $Re = 5.7 \times 10^5$, these peaks are discrete with respect to $F^+$. For $Re = 9.4 \times 10^5$ (Figure 8d,h), the increase in $C_L$ depends on the AoA and $F^+$, and the effect of DBD-PA actuation switches between positive and negative effects. At this $Re$ number, for a $16–19^\circ$ AoA, $C_L$ decreased under almost all conditions. However, for higher angles of attack, there are some conditions in which $C_L$ increases depending on $F^+$. The most effective increase in $C_L$ was obtained in the range of the AoA corresponding to the red range in Figure 8a–d.

Figure 8e–g for $Re = 1.9 \times 10^5–5.7 \times 10^5$ show that the flow field with lower $Re$ numbers has a larger increase in $C_L$ closer to the stall AoA. The dependencies of the increase in $C_L$ on the $Re$ numbers and angles of attack are explained as follows: the actuated DBD-PA placed in a flow field adds a body force into the flow field, changing the behavior of the fluids [41,62,63]. We considered the body force to be almost constant because the power consumption of DBD-PA was fixed in the current experiments. Therefore, the DBD-PA actuation is considered more effective with respect to the control of the flow field at a lower $Re$ number, with a large ratio of the body force generated by the actuation to the main flow momentum. In addition, the result in which the flow field in the region of the AoA corresponds to the red region in Figure 8a–c shows a larger increase in $C_L$ than in the other regions, thereby indicating that DBD-PA is more effective in controlling the stall when the body force is placed closer to the point of the boundary layer separation on the suction side of the wing. Considering that the condition when the separation point is set closer to the trailing edge (i.e., the blue region of the AoA in Figure 8b–d), the increase in $C_L$ is discretely dependent on the condition. These results imply that there is a different reason for the increase in $C_L$. 
Figure 8. $C_L$ curves with $F^+ = 0.1, 1, 10,$ and 100 and without DBD-PA actuation for each Re number (a–d), and $C_L$ increase with respect to $F^+$ and the angle of attack with DBD-PA actuation for each Re number (e–h).
3.3. Particle Image Velocimetry for Characterizing the Flow Field

In this study, the velocity field on the negative pressure side of the wing was observed using a PIV method at a 24° AoA. The mechanism by which the DBD-PA actuation controls the flow field and the increase in $C_L$ was investigated in more detail using this visualization. This AoA was adopted because there are conditions of $F^+$ with a peak of $C_L$ increase at angles of attack of 20°–25° for all $Re$, as shown in Figure 8f–h. Investigating these conditions enabled us to determine the mechanism of flow control with high efficiency. Both the second and third flow patterns, represented as the red and blue areas in Figure 8a–d, respectively, were present at ~24°. Investigating these conditions enabled us to determine the flow control mechanism for different positions of the boundary layer separation. Furthermore, a 24° AoA was carefully selected to ensure that $C_L$ was less affected by the hysteresis caused between the up- and down-sweep motions of the AoA, regardless of the flow pattern and $Re$, as shown in Figure 6.

Figure 9a,b illustrate the distributions of the time-averaged $x$-component of the flow velocity, $\bar{u}$, and turbulent kinetic energy (TKE), respectively. These were calculated from 1000 image pairs of instantaneous velocity distributions measured using PIV. The conditions were $F^+ = 1$ with $Re = 9.4 \times 10^5$. The direction of the main flow was from left to right, and the wing model is shown in these images up to 66% of the chord length. Figure 9a shows that the separation point of the boundary layer is estimated as 0.16$c$; furthermore, it shows that the wing surface is covered by a recirculation zone. A shear layer, shown as a change in contour color in Figure 9a, is formed between the main flow and the recirculation. This layer overlaps with a region with a large TKE value, as shown in Figure 9b. This TKE region starts immediately upstream of the separation point of the boundary layer. The shear layer thickness is shown in Figure 9a, which is defined as the distance between the position of $u/u_\infty = 0$ and the outer edge of the shear layer at a certain chord position. The high-TKE regions in Figure 9b become wider with an increase in the distance from the separation point downstream.

Figure 9. PIV results for a typical flow field around the NACA0015 wing model at an angle of attack of 24° (top), and magnified images of the PIV result near the separation point of the boundary layer (bottom). The conditions in this figure are $F^+ = 1$ and $Re = 9.4 \times 10^5$. 
In this study, the characteristics of the flow field were investigated by calculating the following four indices using the velocity, TKE, and $C_L$ data. (1) The $C_L$ increase ratio $K_{CL}$: this index was calculated by normalizing the $\Delta C_L$ with the $C_L$ without DBD-PA actuation in the same flow condition. The $K_{CL}$ is defined as follows:

$$K_{CL} = \frac{C_L}{C_{L,NoPA}} - 1,$$

where $C_L$ and $C_{L,NoPA}$ are the lift coefficient with and without DBD-PA actuation at a 24° AoA, respectively. A total of 28 data points were calculated considering all $F^*$ and $Re$ number conditions in this study. (2) The ratio of the shear layer height $K_h$: to calculate the ratio of the shear layer height, the $\xi$ axis was defined in the direction parallel to the chord line of the wing, and the $\eta$ axis was defined in the direction perpendicular to the $\xi$ axis, considering the origin of the coordinates at the leading edge of the wing, as shown in Figure 9a. Figure 10 shows the velocity profile of the $\xi$-component along the axis parallel to this $\eta$ axis on the wing surface obtained at $\xi/c = 0.2, 0.325,$ and 0.45. The momentum thickness was calculated at several $\xi/c$ values, and the shear layer height was defined as the momentum thickness at $\xi/c = 0.45$. The change in the momentum thickness with respect to the chord direction was approximately linear. $\xi/c = 0.45$ was adopted because the position corresponding to $\xi/c = 0.45$ provides the most accurate estimation of the momentum thickness, and the positions downstream from $\xi/c = 0.45$ were not adopted because there exist conditions under which the freestream region was not included in the field of vision. The ratio of the shear layer height, $K_h$, was defined as the value of the change in shear layer height due to DBD-PA actuation normalized by the height without actuation; this index is expressed by the following formula:

$$K_h = \frac{h}{h_{NoPA}} - 1,$$

where $h$ and $h_{NoPA}$ are the shear layer height with and without DBD-PA actuation at $\xi/c = 0.45$ and AoA = 24°, respectively. (3) The ratio of increase in the maximum TKE $K_{TKE}$: to calculate the ratio of increase in the maximum TKE, a TKE profile was obtained at $\xi/c = 0.45$, similar to the procedure for calculating the velocity profile described above; a maximum TKE value was extracted in that profile. This index was defined as the value of the maximum TKE increased by DBD-PA actuation divided by the value without actuation. The $K_{TKE}$ is defined as follows:

$$K_{TKE} = \frac{TKE}{TKE_{NoPA}} - 1,$$

where $TKE$ and $TKE_{NoPA}$ are the maximum turbulent kinetic energy with and without DBD-PA actuation at AoA = 24° and on a line perpendicular to the chord at $\xi/c = 0.45$, respectively. (4) The normalized displacement of the separation point of the boundary layer $ND_{SP}$: the normalized displacement of the separation point of the boundary layer was determined as follows: velocity profiles in the direction perpendicular to the wing surface were calculated for each position along the chord. The velocity was evaluated along a vector tangential to the airfoil surface. The separation point was defined as the most upstream chord position where a velocity profile with a negative value was found. The displacement was defined as the result of subtracting the position of the separation without actuation from the position of the separation with actuation. As chord lengths were used for normalization, the $ND_{SP}$ is expressed as follows:

$$ND_{SP} = \frac{\xi_{SP} - \xi_{SP,NoPA}}{c},$$

where $\xi_{SP}$ and $\xi_{SP,NoPA}$ are the position of the separation with and without DBD-PA actuation, respectively. $c$ is the chord length of the wing model.
3.4. Dependence of the Four Indices on Re and $F^+$ under a Deep Stall Condition with DBD-PA Actuation

The discussion is based on the data for each of the four indices defined in the previous section, which are summarized in the color maps in Figures 11–14. These figures, with the Re number on the x-axis and the normalized burst frequency, $F^+$, of the plasma actuation on the y-axis, show the values of the indices defined by a color bar. The asterisks in Figures 11–14 indicate the conditions for which data was obtained by PIV measurement, and the results of the conditions indicated by triangle marks are discussed in the next section. Figure 11 shows a contour map of the $C_L$ increase ratio by DBD-PA actuation, named the first index in the previous section, at a 24° AoA. The broken line in the figure connects the data points of the maximum value of each Re. Figure 11 illustrates the region where increases in $C_L$ clearly exist in the range of $F^+ = 0.1 - 5.0$ and their peak exists at $F^+ = 0.5$ or 1.0. Furthermore, the value shows a ridge at $F^+$ between 10 and 100 with Re between $4.2 \times 10^5$ and $5.7 \times 10^5$. The following discussion focuses on the phenomena that cause the characteristics of this index, as shown in Figure 11, based on the dependence of the other three indices on Re and $F^+$. 

![Figure 10. Schematic defining the position of the boundary layer separation on the $\xi$ axis.](image1)

![Figure 11. $C_L$ increase ratio.](image2)
Figure 12 shows a contour map of the increase ratio of the maximum TKE by DBD-PA actuation, which is referred to as the third index in the previous section. According to Figure 12, the $F^+$ of the point where the value of the index is the largest exists between 0.1 and 1.0 for each $Re$ number condition and decreases drastically with an increase in the $Re$ number. This result implies that higher energy vortices are effective in producing larger disturbances and turbulence with an increase in the $Re$ number, similar to the flow energy. The energy of each vortex is related to the input energy allocated to each burst wave when the vortices originate from the burst actuation of the DBD-PA. In this study, the time-averaged input power for all experimental conditions was uniform; therefore, a greater input energy was allocated to a single burst wave in the case of a smaller $F^+$. Consequently, a higher $Re$ number requires a smaller $F^+$ value to achieve a larger TKE.

![Figure 12. Maximum TKE increase ratio.](image12)

Furthermore, Figure 15a,b show the instantaneous vorticity fields and velocity vectors at $Re = 1.9 \times 10^5$ with $F^+ = 1$ and at $Re = 4.2 \times 10^5$ with $F^+ = 0.5$, respectively. Under both conditions, the maximum TKE increase ratio exhibits a high peak (Figure 12). Both flow fields are observed under DBD-PA actuation with a low $F^+$, indicating that one or two vortices with a large negative vorticity are shed into the shear layer formed by the boundary layer separation near the leading edge. Both flow fields are frequently observed in the instantaneous PIV results under both conditions, which supports the consideration of high-energy vortices generated by DBD-PA actuation. The PIV data in this study had an insufficient time resolution; therefore, further studies using high-speed PIV or a phase-locked method are required to directly confirm from the PIV results that these vortices are generated synchronously by DBD-PA actuation. Considering the region where the third index is high, a comparison of Figures 11 and 12 illustrates that the conditions of $Re$ and $F^+$ with indices greater than 1.5 are relatively close in the bottom-left region in these figures. In contrast, from the same comparison at the region where the third index is less than 1.5, the first index increase found in the previous paragraph is not fully accounted for by the ridge of the third index, e.g., at $Re = 4.2 \times 10^5$ with $F^+ = 10$, $Re = 5.7 \times 10^5$ with $F^+ = 50$, and $Re = 5.7 \times 10^5$ with $F^+ = 0.5$ and 1.0.

Figure 13 highlights the effectiveness of the DBD-PA based on the change in the shear layer height behind the separation point with and without actuation, i.e., the second index. The blue region in this figure, where the shear height ratio is negative, indicates a flow field in which the momentum of the flow near the wing surface recovers because the shear layer approaches the wing. Figure 13 illustrates that a higher $F^+$ effectively changes the velocity profile of the shear layer and recovers the momentum on the wing surface.
compared to a lower $F^+$; the values of the most effective $F^+$ are within 10 and 50. A higher $C_L$ increase ratio can be obtained by increasing the momentum around the wing, i.e., a higher negative value of the shear layer height ratio. The pattern shown in Figure 13 is different from the pattern in Figure 11, except at the high $F^+$ of $Re = 4.2 \times 10^5$ and $5.7 \times 10^5$. For a low $F^+$, a large value of the $C_L$ increase ratio is also found for $Re = 5.7 \times 10^5$ at $F^+ = 0.5$ or 1.0; however, the ratio of the shear layer height is close to zero, and there is a small increase in the TKE in this region. This reasoning is insufficient to fully comprehend these phenomena.

![Figure 13. Ratio of the shear layer height.](image)

Figure 14 shows the normalized displacement of the boundary layer separation point with and without actuation, i.e., the fourth index. The region with a higher value of this index illustrates that the boundary layer separation at the leading edge is suppressed by the DBD-PA actuation, and the attached area is clearly extended, especially at $Re = 4.2 \times 10^5$ and $5.7 \times 10^5$. In these red areas, the separation point of the boundary layer moves downstream, and the acceleration of the flow near the leading edge is enhanced. Thus, the negative $C_p$ around the leading edge increases and $C_L$ is enhanced, as shown in Figure 11. One of the reasons for the increase in $C_L$ caused by plasma actuation in the red area in Figure 14 is the shift in the separation point of the boundary layer downstream. A comparison of Figures 13 and 14 illustrates that the red area in Figure 14 and the blue area in Figure 13 for $Re = 4.2 \times 10^5$ and $5.7 \times 10^5$ are not in identical positions. That is, the changes in each index are similar in the high $F^+$ region but different in the low $F^+$ region. The disturbance generated by the DBD-PA increases the momentum of the boundary layer near the leading edge of the wing at a specific $Re$ without depending on $F^+$. Therefore, it effectively suppresses the boundary layer separation without attracting the shear layer.
Figure 14. Normalized displacement of the separation point of the boundary layer on the wing model with and without DBD-PA actuation.

Figure 15. PIV results of vorticity fields and velocity vectors for typical flow fields with DBD-PA actuation.

These results imply that the increase in $C_L$ caused by DBD-PA actuation is attributed to three phenomena that occur individually or in combination:
1. Increases in TKE in the shear flow on the suction side of the wing.
2. Momentum recovery in the flow field on the wing caused by the shear layer being attracted to the wing surface.
3. Acceleration of the flow around the leading edge.

In (1), a high TKE indicates the presence of high-energy vortices generated in the shear layer. The low pressure area caused by the rotation of these vortices can improve the wing lift. In (2), DBD-PA actuation places disturbances and vortices into the shear layer, promoting momentum exchange between the mainstream and recirculation zones, resulting in momentum recovery. In addition, momentum recovery occurs when the shear layer moves to the wing surface because of the movement of the separation point of the boundary layer downstream on the suction side of the wing owing to the disturbance or acceleration by DBD-PA actuation. These two momentum recovery methods cause an
increase in the $C_L$. In (3), the DBD-PA actuation enhances the disturbance in the boundary layer at the leading edge of the wing, and such a disturbed boundary layer is more resistant to flow separation, enabling a longer distance for the boundary layer attachment. Thus, a longer distance results in a large negative $C_p$ area around the leading edge, thereby increasing $C_L$. This consideration of the disturbance enhancement in the boundary layer with DBD-PA actuation is supported by the comparison results between the positive displacement for $Re = 1.9 \times 10^5$–$5.7 \times 10^5$ and the negligible displacement for $Re = 9.4 \times 10^5$ in Figure 14. The boundary layer at the leading edge of the wing is considered laminar in the former $Re$ number conditions, whereas it is considered turbulent in the latter $Re$ number conditions [39,64]. Considering the relationship between these boundary layer conditions and the directions of displacement, and the well-known principle that the turbulent boundary layer is more resistant to flow separation than the laminar boundary layer, a laminar–turbulent transition of the boundary layer by plasma actuation occurs in the major region of the positive displacement in Figure 14.

Given these considerations, the second and third phenomena do not increase with plasma actuation at $Re = 9.4 \times 10^5$ if the boundary layer has already transitioned to a turbulent flow and grown sufficiently thick without plasma actuation.

3.5. Change in the Velocity Field Caused by DBD-PA Actuation

Under the experimental conditions indicated by the triangular marks in Figures 11–14, the four indices presented in the previous section have relatively large values; therefore, these conditions are selected for the following discussion. Table 2 summarizes the values of $Re, F^*$, and the four indices under these conditions. Figure 16 shows the time-averaged velocity field obtained using the PIV method, and Figure 17 shows the $C_p$ distribution under the same conditions as those in Figure 16.

<table>
<thead>
<tr>
<th>$Re$ ($\times 10^5$)</th>
<th>$F^*$</th>
<th>$K_{CL}$</th>
<th>$K_{TKE}$</th>
<th>$K_h$</th>
<th>$ND_{SP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>1.0</td>
<td>0.709</td>
<td>3.28</td>
<td>0.382</td>
<td>-0.005</td>
</tr>
<tr>
<td>4.2</td>
<td>0.50</td>
<td>1.06</td>
<td>3.32</td>
<td>0.149</td>
<td>0.150</td>
</tr>
<tr>
<td>4.2</td>
<td>10</td>
<td>0.511</td>
<td>0.778</td>
<td>-0.573</td>
<td>0.190</td>
</tr>
<tr>
<td>5.7</td>
<td>1.0</td>
<td>1.14</td>
<td>1.47</td>
<td>-0.115</td>
<td>0.145</td>
</tr>
<tr>
<td>5.7</td>
<td>50</td>
<td>0.501</td>
<td>0.509</td>
<td>-0.383</td>
<td>0.190</td>
</tr>
<tr>
<td>9.4</td>
<td>1.0</td>
<td>0.151</td>
<td>0.213</td>
<td>0.274</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

Figure 16a,c,f,i show the results without DBD-PA actuation. These results indicate that the boundary layer is separated near the leading edge of the wing, and almost the entire suction side surface of the wing is covered by a recirculation region for (a) $Re = 1.9 \times 10^5$, (c) $4.2 \times 10^5$, and (f) $5.7 \times 10^5$. The boundary layer separates once at the leading edge of the wing for (i) $Re = 9.4 \times 10^5$; however, the formed separation bubble is very small, and the boundary layer immediately reattaches near the leading edge. Figure 16i also shows that the boundary layer attaches to approximately 20% of the chord length from the leading edge of the wing, where the attached flow region is longer than that under other conditions. These results imply that the boundary layer may be turbulent downstream of the reattachment point [39].

The other panels in Figure 16 present the typical results with the DBD-PA actuation; the characteristic phenomena can be observed in these figures. For example, Figure 16b presents the result at $Re = 1.9 \times 10^5$ with $F^* = 1$. The shear layer generated by the boundary layer separation at the leading edge shifted slightly toward the wing surface, and the shear layer thickness increased because of DBD-PA actuation. In addition, the TKE in the recirculation region increased significantly. Figure 16d presents the result at $Re = 4.2 \times 10^5$
with $F^* = 0.5$. The trends in change caused by actuation shown in this figure are similar to those in Figure 16b; however, they are emphasized further, i.e., the shear layer thickness increases significantly and the TKE shows a very high value occupying the entire recirculation region. Figure 16e presents the result obtained when $Re = 4.2 \times 10^5$ with $F^* = 10$, and the shear layer clearly shifts toward the wing surface. The recirculation zone cannot be observed in the average velocity distribution in the area between the wing surface and shear layer, and the TKE in the same area increases slightly. Furthermore, the position of the boundary layer separation moved downstream, and no boundary layer separation was observed at the leading edge. Figure 16f shows the results obtained when $Re = 5.7 \times 10^5$ and $F^* = 1$. The shear layer clearly shifts toward the wing surface, and the thickness increased slightly. The TKE in the area overlapping the shear layer also increased. The position of the boundary layer separation moved downstream from the leading edge. Figure 16g shows that the shear layer shifts further toward the wing surface than in Figure 16f and at $Re = 5.7 \times 10^5$ with $F^* = 50$, whereas the increase in TKE is smaller than that in Figure 16f. Similar to Figure 16e,g, the boundary layer separation at the leading edge was prevented. Figure 16j presents the result obtained for $Re = 9.4 \times 10^5$ with $F^* = 1$. The position of the shear layer moved slightly away from the wing surface with DBD-PA actuation in a different manner from the other conditions with a low Re number. The TKE of the shear layer increased, similar to that under the other conditions. The figure also indicates that the separation point of the boundary layer hardly changes, suggesting that DBD-PA has little effect on the enhancement of momentum exchange and separation suppression in the turbulent boundary layer in high-Reynolds-number conditions.
Figure 16. Comparison of PIV results that show changes in flow pattern by DBD-PA actuation.

Figure 17 shows $C_p$ distributions on the wing surface under the same conditions as those shown in Figure 16. The red arrows in this figure denote the separation point of the boundary layer, i.e., the starting position of the recirculation region evaluated based on the PIV results. Without actuation, a flat distribution was observed in most areas on the suction side surface with a negative $C_p$ because the flow separates, and a separate area with recirculation is formed in the downstream region of the separation point on the suction side surface. The upstream edge of the flat region indicates the separation point; therefore, the flow is separated at the leading edge, as shown in Figure 17a $Re = 1.9 \times 10^5$, (b) $4.2 \times 10^5$, and (c) $5.7 \times 10^5$, and the separation point moves downstream, as shown in Figure 17d $9.4 \times 10^5$. The change in the $C_p$ distribution with DBD-PA actuation was
characterized by considering the relationship between the three indices shown in Figures 12–14 and the $C_p$ distributions shown in Figure 17. Three trends of change correspond to the three phenomena described in the previous sections.

The first trend is observed in the cases of Figure 17a with $F^+ = 1$, (b) $F^+ = 0.5$, and (c) $F^+ = 1.0$, in which a large increase in the TKE is observed in Figure 12. Under these conditions, the negative $C_p$ was enhanced over the entire chord of the suction side surface of the wing. In contrast, the distribution did not exhibit a negative $C_p$ peak at the leading edge. This result corresponds with the first phenomena. The DBD-PA actuation shed high-energy vortices on the suction side surface of the wing, contributing to the growth of the negative $C_p$ on it.

The second trend was observed under all conditions with DBD-PA actuation, as shown in Figure 17, in which the pressure coefficient increased on the pressure side of the wing. This result indicates an increase in circulation around the wing by DBD-PA actuation. All the results cannot be explained in this study; however, one reason for this increase is that the DBD-PA actuation increases the momentum in the flow near the wing by attracting a shear layer to the wing surface, as shown in Figure 13. The increase in $C_p$ at the trailing edge suggests a reduction in the re-circulation region in the wake caused by momentum recovery on the wing surface. Furthermore, the prominent variation on the pressure side was considered affected by the second phenomenon; however, further research that considers the relationship between the changes in the pressure side $C_p$ distribution and the trailing edge flow field is necessary to fully clarify the mechanism behind this trend.

The third trend is observed in the cases of Figure 17b with $F^+ = 10$ and (c) with $F^+ = 50$, where the boundary layer separation is suppressed and the separation point moves downstream, as shown in Figure 14. Both distributions exhibit a negative $C_p$ peak at the leading edge. These enhancements in negative pressure increased the lift. This trend corresponds to the third phenomenon. These results indicate that the first and third trends appear to be independent of each other; however, the second trend can depend on these trends and occur simultaneously.

The two separation points of the boundary layer, evaluated based on the $C_p$ distributions and PIV measurements, were consistent under conditions of high $F^+$, high $Re$, or no DBD-PA actuation. However, it is difficult to determine the separation point in the $C_p$ distributions under relatively low $Re$ and $F^+$ conditions. These results can explain the shedding of high-energy vortices into the flow above the wing because of burst actuation of the DBD-PA under such conditions. According to previous studies [65], a local low pressure area in the $C_p$ distribution flows unsteadily downstream when vortices flow above the airfoil. Simultaneously, the separation point moved unsteadily; therefore, the correspondence between the separation point determined based on the time-averaged PIV results and time-averaged $C_p$ distribution was weakened.
3.6. Mechanisms for Increasing Lift Using DBD-PA Actuation

The two mechanisms of increase in the lift with DBD-PA actuation are assumed to explain all appearances of the three flow phenomena for the increase in \( C_L \) and the three trends for the changes in \( C_p \) distribution that contributed to the increase in \( C_L \) in the present experiment.

In the first mechanism, the DBD-PA sheds high-energy vortices with a very low pressure area at the center of the vortex into shear flow on the suction side of the wing. Enhancing the low pressure on the suction side of the wing reduces a downward force as integrating pressure over a surface. The vortex with a very low pressure area rolled downstream with the flow on the suction side, causing an increase in \( C_L \). The low pressure area explains the first phenomenon and the first trend. Simultaneously, the TKE of the shear layer is increased by the rolling motion of the vortex, and momentum is transported into the flow near the wing surface, corresponding to the enhanced mixing between the recirculation region and freestream. Consequently, an increase in \( C_L \) occurs with velocity recovery above the wing. This increase in TKE caused by the high-energy vortex explains the second phenomena and the second trend.

The second mechanism involves introducing a disturbance into the boundary layer at the leading edge of the wing. This disturbance enhances the laminar–turbulent transition of the boundary layer [66], and it makes the attached distance of the turbulent boundary layer longer than that of the laminar boundary layer, thereby increasing \( C_L \). This increase in the attached distance explains the third phenomenon and the third trend. Simultaneously, the turbulent boundary layer causes an increase in the TKE of the shear layer and promotes momentum transport from the mainstream to the flow near the wing surface, increasing \( C_L \). This increase in the TKE caused by the disturbance in the boundary layer explains the second trend and second phenomena. These descriptions of the two mechanisms do not contradict the discussion based on Figures 11–17. These descriptions are indeed consistent with the independence of the trends discussed in Section 3.5.

Considering the relationship between the results in Figures 13 and 17, an increase in \( C_p \) on the pressure side of the wing occurs when the ratio of the shear layer height is relatively large. In other words, this result implies that an increase in circulation around the wing can occur despite the absence of momentum recovery in the shear flow on the suction side of the wing. The abovementioned mechanisms cannot explain these results; thus, a third mechanism exists.

Fujii et al. investigated the effect of DBD-PA actuation on a low \( Re \) number of \( 6.3 \times 10^4 \) via numerical analysis [61,67]. They found a two-dimensional strong vortex with a large size and a small disturbance related to the unstable mode of the shear layer as the lift increase mechanism, corresponding to the first and second mechanisms explained above in this section, respectively. Moreover, they proposed a third mechanism, momentum injection by induced flow; however, the applicability of this mechanism was not confirmed for a flow with a high Reynolds number or with the burst actuation of DBD-PA, as in the present experiment, because the effect of momentum injection by the induced flow appears significant only when the velocity ratio of the induced flow by DBD-PA actuation to the mainstream is relatively large, as in the case of the continuous-mode actuation of DBD-PA. Thus, further investigation is required to clarify this third mechanism.

4. Conclusions

In this study, parametric experiments for \( F^+ \) with a wide range of \( Re \) values \( (10^5–10^6) \) for NACA0015 airfoil was conducted to identify the multiple flow control mechanisms that exist within the experimental condition. The effects of DBD-PA actuation on the flow field around the wing were investigated by the wind tunnel testing of a 2D wing model (NACA0015) with the DBD-PA mounted on the leading edge. A parametric survey was performed for \( F^+ \) ranging from 0.1 to 100 and \( Re \) values ranging from \( 10^5 \) to \( 10^6 \). The \( C_L \)
The characteristics of the increase in $C_L$ with DBD-PA actuation were organized according to the three flow patterns for the flow before actuation, i.e., (1) the completely attached flow; (2) the partially separated flow along the chord length; and (3) the completely separated flow at the leading edge. DBD-PA was concluded to be more effective in controlling stall when the body force was placed closer to the point of boundary layer separation on the suction side of the wing. The flow control effect is diminished when the DBD-PA is mounted on the leading edge of the wing in the high $Re$ number flow field because the separation point moves downstream due to the laminar–turbulent transition of the boundary layer.

Four indices were then evaluated according to the $C_L$ and the velocity field at $24^\circ$ AoA. Comparing these four indices, three phenomena for the increase in $C_L$ were found: (1) increase in TKE due to shedding of high-energy vortices into the suction side of the wing; (2) increase in circulation around the wing due to the momentum transport being promoted in the shear flow on the suction side of the wing and due to the shear layer being attracted to the wing surface; and (3) acceleration of the flow due to shifting of the separation point of the boundary layer to the downstream at the leading edge. For the $C_p$ distribution, three trends in the features of the distribution correspond to the three phenomena for the increase in $C_L$. These three trends were induced independently or in combination by comparing the $C_p$ distribution under each condition. These results indicate that the first and third trends appear to be independent of each other; however, the second trend can depend on these trends and occur simultaneously.

These phenomena and trends suggest that the actuation of the DBD-PA mounted on the leading edge of the wing has at least two mechanisms for increasing the $C_L$. The first mechanism includes the shedding of vortices with a very low pressure area into the shear flow on the suction side of the wing. The second mechanism introduces a disturbance into the boundary layer at the leading edge of the wing. However, these two mechanisms cannot explain why the circulation may increase when there is no momentum recovery in the shear flow on the wing; therefore, a third mechanism needs to be identified.

In this study, the multiple flow control mechanisms that exist within the experimental condition were identified, especially in high $Re$ number ranges. As the next phase of this study, by verifying that the same flow control mechanism is obtained for the same flow field regardless of the airfoil, it is possible to estimate the optimum control parameter from the flow field that is known by the numerical analysis for any airfoil. There is a need of the further investigation when the method is applied to DBD-PA systems with other types of actuators.

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