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Flying wing flow separation control by microsecond pulsed dielectric barrier discharge at high Reynolds number

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ABSTRACT
In this study, a microsecond pulsed dielectric barrier discharge (μs-DBD) plasma actuator is utilized to improve the aerodynamic performance of a flying wing. The wind tunnel experiments were conducted by the μs-DBD plasma actuator at a high Reynolds number (Re = 2.61 × 10^6). The effects of discharge position and pulse frequency on the flow control performance were studied by force measurements. The particle image velocimetry test was used to reveal the influence of plasma actuation on the detailed velocity field at the suction side of the flying wing. Results show that plasma actuation can significantly improve the aerodynamic performance of the flying wing under high Reynolds number. The best flow control effect is obtained when the plasma actuator is mounted near stagnation point (0.1% C). There is an optimal excitation frequency (100 Hz) at Re = 2.61 × 10^6 (corresponding to the wind speed of 70 m/s), at which the flow instability can be effectively excited. In the optimal situation, the relative improvement of the maximum lift coefficient reaches 20.51% and the stall angle is delayed by 6°. The flow control performance is mainly achieved at the outer part of the wing because the flow separation develops gradually from the wing tip to the root. These experimental results contribute to the free flight test in the wind tunnel and the flight test in real air conditions.

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I. INTRODUCTION

Compared with the conventional layout aircraft, the flying wing layout aircrafts have the outstanding advantages of high aerodynamic efficiency, light weight, large loading space, and good stealth performance and are favored by both military and civil applications all over the world.1,2 With the increasing use of the aviation field, the aircraft of flying wing layout seems to be the seed candidates for future development. Most of flying wing aircraft use tailless layout and swept wing with a blunt leading edge.4 This layout has good aerodynamic performance at high speed and small angle of attack (α). However, at low speed and high angle of attack (such as taking off and landing), its aerodynamic performance is poor.5 At a large angle of attack, asymmetric boundary layer separation of the flying wing leads to great lift loss, drag enhancement, and deterioration of pitching characteristics.6 In addition, the flow separation causes the reduction of the control surface efficiency and maneuverability.5,6,7 The plasma flow control technology can suppress flow separation, increase lift, and reduce drag and noise, thus it is promising for improving the aerodynamic performance and stability of the flying wings.8,9 It has become an important research direction in the aviation field to improve the aerodynamic performance of aircraft at the large angle of attack.10 DBD (Dielectric Barrier Discharge) plasma actuation is one of the promising plasma flow control methods and has the advantages of simple structure, low energy consumption, fast response, and broad frequency bandwidth and has been widely concerned in recent years.11,12
The layout of the DBD plasma actuation system is shown in Fig. 1. It consists of an exposed electrode, an encapsulated electrode, a layer of dielectric, and a high-voltage power supply. Actuated by the strong electric field produced by the high-voltage between the two electrodes, the air at the surface of the dielectric above the encapsulated electrode is ionized and the plasma is generated. When the high-voltage profile is sinusoidal (AC-DBD), the charged particles in the plasma move under the action of the electric field force, inducing an ion wind with the velocity less than 10 m/s. When the high-voltage profile is pulsed with microsecond/nanosecond time scale (μs-DBD/ns-DBD), the ion wind velocity is lower than 1 m/s, but a fast generation of Joule heat will be observed, which can produce strong disturbance in the flow field and suppress the boundary layer separation. The effective free-stream velocity range of μs-DBD/ns-DBD (0.8 Ma) is much larger than that of AC-DBD (0.4 Ma) because of the limited velocity of the ion wind induced by AC-DBD.

There are many research studies using a DBD plasma actuator for flying wing flow control in recent years. Han et al. studied the actuation frequency of ns-DBD to improve the aerodynamic performance of the flying wing at different Reynolds numbers. The results show that there is an optimal actuation frequency, which better delays the rupture of the leading edge vortex. Most of the studies are carried out with small models and comparatively high free-stream velocity, making the test Reynolds number around 105. However, the target condition (taking off and landing) of the plasma flow control is mainly at a relatively low speed and high Reynolds number, which means a large scale experimental model and a large wind tunnel. Whether the DBD plasma actuation is still effective in high Reynolds number (>106), relatively lower speed (<0.3 Ma), and complex wing profile like the flying wing still needs exploration. Therefore, it is necessary to research the plasma flow control with a large scale complex profile at a high Reynolds number for engineering applications.

In this paper, to improve the aerodynamic performance of a “W” flying wing with a span of 2.4 m at a high Reynolds number, wind tunnel experiments with μs-DBD were carried out. The flow control effects of the discharge position and pulse frequency were first studied by force measurements to find the best discharge position and frequency. Subsequently, the flow field over the flying wing was studied by the PIV (Particle Image Velocimetry) flow visualization to investigate the separation patterns at the different Reynolds numbers. The results of the flying wing with plasma actuation obtained in this paper provide an experimental basis for the free flight test in the wind tunnel and the flight test in real air conditions.

II. EXPERIMENTAL SETUP

A. The wind tunnel and flying wing

The experiments were conducted in the FL-51 wind tunnel at the Aerodynamics Research Institute of the Aviation Industry Corporation of China. It is a closed circuit continuous wind tunnel with a test size of 11 m (length) × 4.5 m (width) × 3.5 m (height), as shown in Fig. 2. The maximum wind speed is 100 m/s, and the average turbulence of the test section is less than 0.10%.

A double “W” flying wing model with a span length of 2.4 m and an average aerodynamic chord length (C) of 0.547 m is used in the experiments. The sweep angle of the flying wing is 34.5°, and the aspect ratio is 5.79. The model is made by fiber-reinforced plastic (FRP) with metal skeleton inside. The skeleton is connected to the aerodynamic force measuring balance, and the plasma actuator is pasted on the FRP surface.

The plasma actuator consists of the exposed electrode, encapsulated electrode, and dielectric layer. The electrodes, made of copper tape (0.02 mm thickness), were separated by a Kapton dielectric layer in 0.1 mm thickness. The exposed electrode and the encapsulated electrode were glued to the dielectric layer with zero inner-gap. The width of the exposed electrode and encapsulated electrode is 3 mm and 5 mm, respectively. The microsecond high-voltage pulse power supply is fabricated inside the flying wing to drive the plasma actuator, which is placed at the leading edge of the wing, as shown in Fig. 3. The electrical parameters during the discharge are measured by a P6015A high voltage probe and a DP04104 oscilloscope. The rising time of the voltage profile is 1 μs and the pulse width is 2 μs. The peak to peak voltage is 10 kV.

B. The measuring methods

1. Aerodynamic force measurement

The force was measured by a rod-type six-component strain balance installed inside the flying wing model. The model is
supported with a single-arm abdomen through the balance as shown in Fig. 2. The VXI (VMEbus Extension for Instrumentation) data acquisition system is used for force data acquisition. Seven repetitive tests are conducted for calibration before the experiment to ensure the accuracy of each element of the balance. During the force measurement experiments, the wind speeds of \( v = 50 \text{ m/s} \) and \( 70 \text{ m/s} \) are used, corresponding to the Reynolds number of \( 1.86 \times 10^6 \) and \( 2.61 \times 10^6 \), respectively.

### 2. PIV flow visualization

The Tomo-PIV test system is used to measure the flow field over the flying wing. The laser of the PIV system has single pulse energy of 500 mJ and a wavelength of 532 nm (green light). The CCD camera has 16M pixels (4904 \( \times \) 3280), and the grayscale resolution is 12 bits. The image acquisition frequency is 3.2 fps. System synchronization can be achieved by using a programmable time controller (PTU) with a time resolution of 0.3 ns. PIV data acquisition and processing is performed using Davis 8.3 software. The particles used in the experiments are produced by pressure atomization with olive oil. The particles are about 1 \( \mu \text{m} \) in diameter.

The PIV test collects 50 sets of images at one time, and the final velocity field is calculated from the average of these 50 sets of images. Figure 4 shows the setup of the PIV system. The laser device is mounted at the top of the wind tunnel to generate the laser, which passes through the observation window to illuminate the particles. The camera is placed at the side of the wind tunnel, perpendicular to the laser sheet to capture the movement of the particles.

To observe the influence of the plasma actuation on the flow separation and figure out the flow control mechanism, two streamwise cross sections are selected as shown in Fig. 5. The distance between the longitudinal symmetry plane of the model and the two test sections is 480 mm (profile 1, P1 for short) and 770 mm (profile 2, P2 for short), respectively.

### III. RESULTS AND DISCUSSION

Because of the sensitivity of the flow field and the complex 3D shape of the flying wing, a good actuation position is important to achieve good flow control performance. Previous research found that the flow control effect is sensitive to the actuation position in the chordwise direction and the best actuation position is near the leading edge.\(^\text{6,29}\) Furthermore, for the flying wing, the profile varies greatly spanwise. The spanwise position of the plasma actuator may also influence the flow control effect greatly. Hence, different chordwise and spanwise actuation positions are selected to find a good position to generate good flow control effects for the flying wing.
A. Effect of chordwise actuation positions

Figures 6 and 7 show the maximum lift coefficient variation ($\Delta C_{y_{\text{max}}}$) and stalling angle enhancement ($\Delta \alpha_s$) at different chordwise actuation positions. The dimensionless parameters of $\Delta C_{y_{\text{max}}}/C_{y_{\text{max}}}$ and $c_0 = c_{\text{plasma}}/C$ are shown in Figs. 6 and 7, where $c_{\text{plasma}}$ represents the distance between the wing leading edge and the junction of the two electrodes in the plasma actuator. The negative $c_0$ indicates that the actuator is placed at the pressure side of the flying wing, and the positive value indicates the suction side actuation. The actuator covers the full span of the model with the peak to peak pulse voltage of 10 kV and the pulse frequency of 200 Hz. It can be seen from the curves in Figs. 6 and 7 that the actuation position has a great influence on the flow control effects. The best flow control effects with the plasma actuation are within the position of $c_0 = \pm 0.5\%$ with the maximum lift coefficient increased by 17% and the stall delayed by 5.2°. At other positions, the plasma flow control effects are so weak that can be ignored. Hence, the plasma flow control effects are sensitive to the chordwise actuation position.

To further locate the optimum actuation position, six actuation positions within the position of $c_0 = \pm 0.5\%$ are selected in detail. Figures 8 and 9 show the lift coefficient ($C_y$), drag coefficient ($C_x$), and pitching moment coefficient ($M_z$) curves as a function of the angle of attack at $Re = 1.86 \times 10^6$ and $2.61 \times 10^6$, respectively. When Re is $1.86 \times 10^6$, at the actuation positions of $c_0 = -0.5\%, -0.3\%, -0.1\%, 0.1\%, 0.3\%, 0.5\%$, the maximum lift coefficient of the flying wing can be increased by 0.46%, 4.11%, 11.2%, 15.93%, 14.1%, and 0.38%, respectively, and the stall angle can be delayed by 0°, 0.5°, 4°, 5°, 2.5°, and 0.5°, respectively. When Re is $2.61 \times 10^6$, the maximum lift coefficient of the flying wing can be increased by 0.03%, 0.43%, 9.94%, 15.31%, 6.60%, and 0.22%, respectively, and...
the stall angle can be delayed by $0^\circ$, $0^\circ$, $4.5^\circ$, $5^\circ$, $2.5^\circ$, and $0.5^\circ$, respectively.

Within the actuation positions tested, the best lift enhancement and stall delaying performance appears when $c_0$ is $-0.1\%$ and $0.1\%$, respectively. The pitching moment characteristics can be best improved when $c_0$ is $-0.2\%$, $-0.1\%$, and $0.1\%$, with the rapid decreasing of the pitching moment coefficient delayed by about $2^\circ$.

The reason why the flow control performance is better in the vicinity of the leading edge stagnation point is that the microsecond pulse plasma actuation mainly acts on the flow field in the form of microscale disturbance. When the actuation position is backward, the microscale disturbance is submerged in the well-developed thick boundary layer and the disturbance has no effect on the external flow. When the actuator is near the stagnation point, the boundary layer has just developed, and the microscale disturbance can be easily coupled into the external flow of the boundary layer and promote the mixing between the boundary layer and main flow. The initial structure of the boundary layer is changed, and the boundary layer is accelerated by the plasma actuation, thus suppressing the flow separation and improving the aerodynamic performance of the flying wing.

**B. Effect of spanwise actuation positions**

To investigate the effects of different spanwise actuation positions to the flow control performance, the plasma actuators are arranged at the outer wing section ($605 \text{ mm} < d < 1192 \text{ mm}$), middle wing section ($304 \text{ mm} < d < 605 \text{ mm}$), and inner wing section ($0 \text{ mm} < d < 304 \text{ mm}$) of the model, with the take-off and landing configuration of the flying wing at $\text{Re} = 1.86 \times 10^6$. These three sections are shown in Fig. 10. It is shown in Fig. 11 that the flow control effects of the plasma actuator arranged on the outer wing section is close to that with full-span actuation and is much better than that of the middle wing section and the inner wing section.

The main reason is that the outer wing section is the starting part for the separation of the flying wing, in which the disturbance generated by the plasma actuation can produce the flow control effects over the entire angle of attack range.

When the angle of attack, which is between $14^\circ$ and $16^\circ$, is right larger than the baseline stalling angle ($\alpha_s$), flow separation is well developed at the outer wing section, while there is still attached flow in the middle and inner wing sections. Therefore, the plasma actuation at the outer wing section can suppress the flow separation and improve the aerodynamic performance, while the actuation in the middle and inner wing sections cannot generate the flow control effect because no separation is needed to be controlled there.

When the angle of attack becomes larger ($16^\circ < \alpha < 19^\circ$), the flow separation at the outer wing section becomes serious. There is a good flow control performance with the outer wing section actuation, but the lift enhancement keeps decreasing because of the worsening flow separation. For the middle and inner wing sections, flow separation appears, but the separation is much weaker than that of the outer wing section, so the flow control performance of the outer wing actuation is still better.

When the angle of attack becomes much larger ($\alpha > 19^\circ$), the separation at the outer wing section becomes serious and difficult to control. Thus, the flow control effect of the outer wing actuation weakens. The much stronger separation appears in the middle and inner wing sections, so the lift enhancement becomes obvious with the middle and inner actuation. With the further increase in the angle of attack, the flow separation at all span becomes serious, and the plasma actuation loses flow control ability in that condition. The lift decreases, independent of all the actuation positions.
C. Effect of pulse frequency

Previous research found that the flow control effects of the DBD plasma actuator are closely linked with the relationship between the pulse frequency and the inherent frequency of the flow field. When these two frequencies are well coupled (with the reduced frequency $\hat{f} = f \cdot C / v = 1$), good flow control effects can be obtained on the airfoil. Therefore, experiments were conducted with different pulse frequencies to verify this rule of frequency on the flying wing model at a high Reynolds number and finally the optimum pulse frequency was found.

Figures 12 and 13 show the enhancement of the aerodynamic performance with different pulse frequencies at the Reynolds number of $1.86 \times 10^6$. The plasma actuator with the actuation voltage of 10 kV is mounted full spanwise at the leading edge. It can be seen from the curves that the best flow control performance appears when the pulse frequency is in the range of 50–300 Hz. When the pulse frequency is 100 Hz, the lift coefficient enhancement is maximized. When the pulse frequency is higher than 300 Hz, the flow control effect becomes relatively poor.

To further ascertain the optimum pulse frequency, three pulse frequencies within the section of 50–300 Hz are selected in detail. Figures 14 and 15 show the aerodynamic performance with different pulse frequencies ($f = 100 \text{ Hz}, 200 \text{ Hz}, 300 \text{ Hz}$) at the Reynolds number of $1.86 \times 10^6$ and $2.61 \times 10^6$, respectively. At the Reynolds number of $1.86 \times 10^6$, the maximum lift coefficients with the pulse frequencies of 100 Hz, 200 Hz, and 300 Hz are increased by 20.26%, 15.93%, and 11.55%, and the stall angles are delayed by $5^\circ$, $5^\circ$, and $3^\circ$, respectively. At the Reynolds number of $2.61 \times 10^6$, the maximum lift coefficients with the pulse frequencies of 100 Hz, 200 Hz, and 300 Hz are increased by 20.51%, 15.31%, and 6.85%, and the stall angles are delayed by $6^\circ$, $5^\circ$, and $2^\circ$, respectively. With all the three pulse frequencies used, the plasma actuation can delay the decreasing point of the pitching moment by about $2^\circ$.

It can be seen that the flow control effect is the best when the pulse frequency is 100 Hz. The reason is that the frequency of 100 Hz angle of attack at the outer wing section is larger than that at the middle and inner sections, which produces the better flow control performance.
FIG. 15. Aerodynamic performance with different pulse frequencies at $Re = 2.61 \times 10^6$: (a) lift coefficient, (b) drag coefficient, and (c) pitching moment coefficient.

FIG. 16. The velocity field at the suction side of the flying wing at cross section P1 ($Re = 1.53 \times 10^6$).
is closest to the shedding frequency of the leading edge shear layer at the large angle of attack, which acts as a frequency coupling between the unsteady disturbance of the plasma actuation and the inherent frequency of the flow field. The rule of frequency coupling keeps its validity with the flying wing at the high Reynolds number.

D. PIV flow visualization and the flow control mechanism

1. PIV flow visualization at different cross sections

To figure out the influence of plasma actuation on the detailed velocity field of the flying wing at the high Reynolds number, a PIV flow visualization was carried out at the Reynolds number of $1.53 \times 10^6$. The plasma actuator, with the pulse voltage and frequency of 10 kV and 100 Hz, respectively, is mounted full spanwise at the leading edge.

Two PIV test cross sections (P1 and P2) are shown in Fig. 5. Figure 16 shows the PIV test results at cross section P1 with different angles of attack. It can be seen that when $\alpha = 10^\circ$ and $12^\circ$, the boundary layer separation has not appeared, as shown in Figs. 16(a) and 16(c). The influence of plasma actuation on the flow field is not obvious, as shown in Figs. 16(b) and 16(d). When $\alpha = 14^\circ$, a large separation bubble [Fig. 16(e)] appears at the leading edge, and the separation bubble disappears [Fig. 16(f)] after the plasma

![PIV flow visualization](image-url)
actuation is turned on, indicating that the boundary layer separation is suppressed effectively.

Figure 17 shows the PIV test results at cross section P2 with different angles of attack. It can be seen that the boundary layer is attached when \( \alpha = 10^\circ \) and the plasma actuation has little effect on the flow field, as shown in Figs. 17(a) and 17(b). A separation bubble appears when \( \alpha = 12^\circ \), as shown in Fig. 17(c). After the plasma actuation is turned on, the separation bubble disappears and the boundary layer is attached completely to the wing surface, as shown in Fig. 17(d). When \( \alpha = 14^\circ \), the boundary layer separation becomes much more serious, as shown in Fig. 17(e). After the application of plasma actuation, the separation zone disappears and only a small separation bubble exists in the middle of the wing surface, as shown in Fig. 17(f).

It can be seen from the above analysis that, with the increase in the angle of attack, the flow separation at the outer section of the flying wing (P1) appears earlier than that at the inner section (P2). The plasma actuation can effectively suppress the flow separation of the flying wing. Combining the PIV results with the force measurement results, the following process of the plasma flow control can be figured out.

![Image of PIV test results with different angles of attack](image-url)
At a small angle of attack ($\alpha = 10^\circ$), there is no obvious separation on the surface of the flying wing and the plasma actuation has little effect on the flow field because no separation is needed to be suppressed. When the angle of attack becomes larger ($\alpha = 12^\circ$), the flow separation appears at the outer section of the wing, while there is no obvious separation at the middle and inner sections. Therefore, after the plasma actuation, the separation at the outer section (P1) is suppressed effectively, but the flow field at the middle and inner sections (P2) is hardly changed. When the angle of attack becomes much larger ($\alpha = 14^\circ$), there is obvious flow separation at all span of the flying wing, but the separation at the outer section is much more serious than that at the middle and inner sections. As a result, the relatively weak separation at the middle and inner sections is suppressed effectively while that at the outer section cannot be completely suppressed by the plasma actuation, which makes the flow control performance of the outer wing section actuation decrease and that of the middle and inner sections increase at the large angle of attack. Because the flow visualization only shows the local velocity field of two cross sections, the angle of attack of the lift coefficient variation in the aerodynamic force measurement is not completely matched with the local flow field visualization. The local angle of attack of flow separation in flow visualization is smaller than that of the aerodynamic force measurement.

**FIG. 19.** The velocity field at cross section P2 of the flying wing ($Re = 1.02 \times 10^6$).
2. PIV flow visualization at medium Reynolds number

To further study the influence of plasma actuation on the detailed flow field of the flying wing at smaller Reynolds number and larger angle of attack range, the PIV flow visualization was carried out at the Reynolds number of 1.02 × 10^6, which corresponds to the lower free-stream velocity (v = 27.3 m/s) and acts as a bridge between the Reynolds number in previous research (about 10^{11}) and the upper limit Reynolds number in this study (2.61 × 10^6). The plasma actuator, with the pulse voltage and frequency of 10 kV and 100 Hz, respectively, is mounted full span at the leading edge.

Figure 18 shows the velocity field at cross section P1 of the flying wing with the angle of attack ranging from 6° to 20°. When the angle of attack is no larger than 10° (6° ≤ α ≤ 10°), there is no obvious flow separation on the wing, as shown in Figs. 18(a), 18(c), and 18(e). The flow field changes little before and after the plasma actuation, as shown in Figs. 18(b), 18(d), and 18(f). When 12° ≤ α ≤ 16°, there is obvious flow separation and the plasma actuation can effectively suppress the separation. At α = 12°, as shown in Fig. 18(g), weak flow separation appears. When the plasma actuation is turned on, the flow separation is suppressed completely, as shown in Fig. 18(h). At α = 14°, the separation becomes larger as shown in Fig. 18(i). The plasma actuation can still suppress the separation, but the low-speed region near the wing surface is larger than that at α = 12°, as shown in Fig. 18(j). At α = 16°, the separation becomes serious as shown in Fig. 18(k). Plasma actuation cannot suppress the separation completely, but the separation can be weakened by the plasma actuation, as shown in Fig. 18(l). When α ≥ 18°, more serious separation appears [as shown in Figs. 18(m) and 18(o)] and there is no difference before and after plasma actuation [as shown in Figs. 18(n) and 18(p)]. Plasma actuation can no longer suppress the separation.

It can be seen from the analysis above that there is a proper angle of attack range for the plasma actuation to suppress flow separation of the flying wing. Beyond the angle of attack range, the plasma actuation has no effects on the separated flow field. For the μ-DBD with the pulse voltage and frequency of 10 kV and 200 Hz at Re = 1.02 × 10^6 in this study, this angle of attack range is 12° ≤ α ≤ 16°.

Besides, comparing the velocity field variation of P1 at the Reynolds number of 1.02 × 10^6 and 1.53 × 10^6, it can be seen that the flow separation is more serious at Re = 1.02 × 10^6 than that at Re = 1.53 × 10^6 at the same angle of attack with no plasma actuation. However, when the plasma is turned on, the separation at Re = 1.02 × 10^6 becomes weaker than that at Re = 1.53 × 10^6. This is because the boundary layer is more difficult to be separated at the high Reynolds number with no plasma actuation. However, when the plasma actuation is turned on, the disturbance (fast gas heating) produced by the plasma actuation can generate a stronger influence at the smaller Reynolds number. Therefore, the separation is weaker at Re = 1.02 × 10^6 than that at Re = 1.53 × 10^6 with the plasma actuation on.

Figure 19 shows the velocity field at cross section P2 of the flying wing at Re = 1.02 × 10^6. The same phenomenon as that at Re = 1.53 × 10^6 can be observed by comparing the flow field at P1 and P2. The flow separation appears at a smaller angle of attack and is more serious at P2 than that at P1 at the same angle of attack, as shown in Figs. 19(a), 19(c), and 19(e). This phenomenon makes the outer wing plasma actuation to have a better flow control performance than the middle and inner wing plasma actuation, which verified the rule described in the upper section at a smaller Reynolds number, as shown in Figs. 19(b), 19(d), and 19(f).

Comparing the velocity field variation of P2 at Re = 1.02 × 10^6 and Re = 1.53 × 10^6, the flow separation is also more serious at Re = 1.02 × 10^6 than that at Re = 1.53 × 10^6 with the same angle of attack with the plasma off. Although the difference of the plasma on condition is not obvious, this can also be a half verification of the rule illustrated above at cross section P2.

IV. CONCLUSION

In this paper, the microsecond pulsed dielectric barrier discharge (μ-DBD) plasma actuator is utilized to improve the performance of the large aspect ratio flying wing at a high Reynolds number of 2.61 × 10^6. The force measurement and PIV flow visualization are conducted. Compared with previous studies, the experimental Reynolds number is significantly improved and the experimental condition is closer to real flights, which advances the engineering application of the plasma flow control. The following conclusions are obtained:

1. The best plasma actuation position is in the vicinity of the leading edge stagnation point (0.1% C), and the flow control performance is mainly produced by the plasma actuation at the outer part of the wing (605 mm < d < 1192 mm). The optimum pulse frequency of the plasma actuation is 100 Hz in this study. At Re = 2.61 × 10^6 (v = 70 m/s), the maximum lift coefficient can be increased by 20.51% and the stalling angle of attack can be increased by 6°.

2. The flow separation of the flying wing gradually develops from the wing tip to the root, which makes the flow control performance of the outer wing actuation better than that of the middle and inner wing actuation.

3. There is a proper angle of attack range for the plasma actuation to suppress flow separation of the flying wing. For the μ-DBD with the pulse voltage and frequency of 10 kV and 200 Hz at Re = 1.02 × 10^6, the range of the angle of attack is 12° < α < 16°.

4. The severity of flow separation increases with increasing Reynolds number without plasma actuation, while the severity of flow separation decreases with increasing Reynolds number with plasma actuation.

In the future, based on the results in this paper, the free flight test in the wind tunnel and the flight test in the real air condition of the large-scale flying wing with plasma actuation will be carried out to further push the engineering application of plasma flow control technology.

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The authors declare no conflict of interest.
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