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Analysis of flow separation control using nanosecond-pulse discharge plasma actuators on a flying wing

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Abstract
Dielectric barrier discharge (DBD) plasma is one of most promising flow control method for its several advantages. The present work investigates the control authority of nanosecond pulse DBD plasma actuators on a flying wing model’s aerodynamic characteristics. The aerodynamic forces and moments are studied by means of experiment and numerical simulation. The numerical simulation results are in good agreement with experiment results. Both results indicate that the NS-DBD plasma actuators have negligible effect on aerodynamic forces and moment at the angles of attack smaller than 16°. However, significant changes can be achieved with actuation when the model’s angle of attack is larger than 16° where the flow separation occurs. The spatial flow field structure results from numerical simulation suggest that the volumetric heat produced by NS-DBD plasma actuator changes the local temperature and density and induces several vortex structures, which strengthen the mixing of the shear layer with the main flow and delay separation or even reattach the separated flow.

Keywords: nanosecond, dielectric barrier discharge, flying wing aircraft, flow separation control

(Some figures may appear in colour only in the online journal)

Nomenclature

- $F$: Body force, N m$^{-3}$
- $Q$: Gas energy source terms, W m$^{-3}$
- $e_t$: Total energy
- $e_{\text{internal}}$: Internal energy of neutral gas
- $e_{\text{kinetic}}$: Kinetic energy
- SL: Span length

1. Introduction

For flying wing, flow separation and vortex breakage at large attack angle are inevitable which will seriously affect the aircraft performance, such as decreased lift, wing flutter and even the loss of aircraft maneuverability. Leeside vortices control is considered to be the effective way to solve such problems of flying wing [1–5]. Under the large angle of attack, relative thickness of the large sweepback flying wing or delta wing is thin with the result that a pair of counter-rotating concentrated vortex will be formed on both sides of the front [3, 6]. A flow field topology of the delta wing is shown in figure 1. Vortices are formed from the separation point and curl to the leading edge along their flowing. Applying actuation at the leading edge can change the strength and structure of the vortices effectively [2, 3, 7, 8].

Flow separation and vortex breakage for such aircraft at large attack angle can be reduced and restrained by means of active flow control. This paper uses nanosecond pulse dielectric barrier discharge (NS-DBD) plasma actuators, which
use partial disturbance to control the overall flow field, to realize the active flow control on flying wing at large attack angle.

According to the different input voltage, DBD plasma actuators can be divided into alternating current DBD (AC-DBD) plasma actuators and nanosecond pulse DBD plasma actuators. The input voltage signal of AC-DBD plasma actuators is an AC signal of which the cycle is generally millisecond level, but NS-DBD plasma actuators input voltage signal is commonly nanosecond level. The flow control mechanism of AC-DBD plasma actuators is to apply a high voltage on the electrodes which causes the gas between two electrodes breakdown and forms plasma (electrons and ions). Plasma gains momentum from the electric field and delivers them to the neutral particles through collision which accelerates the form of ion wind, which is used to control the flow field [9, 10]. AC-DBD plasma actuators have a certain control effect on delaying separation, increasing the lift and reducing the drag in the case of low speed [11–16]. However, conventional AC-DBD plasma actuators jet speed (8 m s⁻¹ level) is difficult to be improved due to the limitation of insulating material properties and plasma generation way. AC-DBD can only be used for low speed flow field (about 30 m s⁻¹ level) [10].

In the last decade, with the development of pulse power technology, NS-DBD plasma actuators becomes the research hot spot. The instantaneous actuation power of NS-DBD plasma actuators is very considerable and releases the joule heat which is several orders of magnitude larger than other plasma actuators is very considerable and releases the joule hot spot. The instantaneous actuation power of NS-DBD technology, NS-DBD plasma actuators becomes the research level

2. Experimental facilities and techniques

2.1. NS-DBD plasma actuator

The NS-DBD actuators used in this paper is shown in figure 2, the anode is exposed on the air and the cathode is encapsulated in the dielectric material. The width and thickness of electrodes are 5 mm and 80 μm, respectively. The dielectric (three layers of 60 μm thick Kapton tape) thickness is 0.18 mm.

The actuator is driven by a nanosecond pulse generator, NPG-15/2000(N), which can be trigged by external signals through an optical-fiber connector. This offers an adjustable discharge voltage and frequency. The max pulse energy is 30 mJ, and the peak-to-peak voltage $V_{pp} = 13–18$ kV at a matched 75 Ω loads. During the present study, the peak-to-peak voltage is $V_{pp} = 15.6$ kV, and the pulse current is 40 A. The energy released duration is about 250 ns. Simultaneous measurements of voltage and current for NS-DBD plasma actuators are shown in figure 3.

2.2. Flying wing model

The schematic diagram of the flying wing aircraft model is presented in figure 3. The span and chord length of the model are 700 mm and 350 mm, respectively. The model used in the numerical simulation (figure 4(b)) is same as in experiment except the position of the balance sleeve (figure 4(a)).

The shear flow of the flying wing comes from its leading edge. Besides the main wing has strong vortices and the outboard wing has three-dimensional flow structure around the airfoil due to large span scale. Therefore, the NS-DBD plasma actuators are arranged on the upper side of the leading edge, from $x/C = 0\%$ to $x/C = 90\%$, for that the vortices and flow separation can be controlled at the same time, as shown in figure 5.

2.3. Wind tunnel and force measurement system

The experiments are conducted in a low-speed closed-loop wind tunnel, as shown in figure 6. The test section dimensions (length × width × height) are $1700 \times 1500 \times 1000$ mm³, and the tunnel is driven by a 90 kW radial blower with a 3–35 m s⁻¹ stable velocity range and a turbulence level of $\varepsilon \leq 0.08\%$. Wind tunnel’s pitch drift angle $|\Delta \alpha| \leq 0.5^\circ$ and its course drift angle $|\Delta \beta| \leq 0.5^\circ$.

A $\varphi 14$ mm beam strain-gauge balance with six components is used in aerodynamic force test experiment. The measurement range of the balance is shown in table 1.

2.4. Flying wing model aerodynamic datum

During the test, the velocity is maintained at 25 m s⁻¹ and the associated Reynold number is $5.8 \times 10^5$ based on the mean
The aerodynamic forces and moments of the flying wing model without active flow control are tested at first. The baseline experiment is repeated seven times and the results of all the tests as shown in figure 7. The deviation is less than 0.24% at small attack angle and less than 0.93% at large attack angle. The average deviation is 0.56%.

The freestream velocity is set at $U_\infty = 25 \text{ m s}^{-1}$ for numerical simulation, which is the same as the experiments. Thus, the modulation frequency $f \approx 70 \text{ Hz}$ corresponds to the Strouhal number $Sr = \frac{Fc}{U_\infty} = O(1)$, which is of the same order as the vortex shedding frequency. This particular frequency can cause a strong coupling between the flow induced by plasma actuation and the free-stream, which strengthens the energy injected into the downstream and stabilizes the shedding vortex, resulting in the reattachment of the flow [26].

3. Numerical simulation

3.1. Fluid flow governing equations

NS-DBD plasma actuators actuate the flow field through the volumetric force (momentum transfer from charged particles to neutral species) and volumetric heat (energy transfer from charged particles to neutral molecules). In the simulation of the flow field, the volumetric force and heat sources are added to the Navier–Stokes bulk flow equations in the form of momentum source and energy source term:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \overrightarrow{U}) = 0,$$

$$\frac{\partial \rho \overrightarrow{U}}{\partial t} + \nabla \cdot (\rho \overrightarrow{U} \overrightarrow{U} + p \overrightarrow{I}) - \nabla \cdot [\tau] = \overrightarrow{F},$$

$$\frac{\partial (\rho e_t)}{\partial t} + \nabla \cdot [(\rho e_t + p) \overrightarrow{U} - ([\tau] \cdot \overrightarrow{U}) - k_0 \nabla T] = Q,$$

where $\rho$ is the fluid mass density, $e_t$ is the total energy of flow which can be written as $e_t = e_{\text{internal}} + e_{\text{kinetic}}$, $k_0$ is the coefficient of heat conduction, $[\tau]$ is the shear stress, $[I]$ is the unit tensor and $p$ is the pressure.

However, the volumetric force is negligibly small for NS-DBD plasma actuators. NS-DBD plasma actuators mainly influence flow field through the volumetric heat [27]. Therefore, the effect of plasma on the energy transferring to air is mainly considered in this paper: heat source term $S$, which is added to the energy equation of Navier–Stokes in the form of heat source power density. Since the discharge time is very short (nanosecond level), the simulation process mainly considers the plasma effect on the flow field after energy input. In consideration of the volumetric force, generated by NS-DBD plasma actuators, is very small, $F$ is equal to 0. The input variables of energy, which are coupled into Navier–Stokes equations as the heat source, are simplified. The released energy is simplified by time average during a pulse (250 ns). Then energy source terms (about $1.3 \times 10^{13} \text{ W m}^{-3}$, as shown in figure 8) are imported into the energy conservation equation of Navier–Stokes in the first 250 ns of the period. After the initial 250 ns, the whole simulation domains do not have any additional energy input variables.

3.2. Simulation of flying wing model

Due to the symmetry shape of the flying wing, semi-modular is used in the numerical simulation process. The commercial code (ANSYS FLUENT) is used in this paper. The structured mesh is about 3 million points. It is based on the Sutherland
formula for viscosity. Boundary layer spacing is estimated by $y^+ = 1$.

The whole numerical simulation domain is compressible ideal gas whose pressure and temperature are 101 325 Pa and 300 K respectively. All of the wall is adiabatic. The actuation duration time is 250 ns.

Roe’ FDS scheme is applied in this paper. The flow discretization is based on second order upwind. The turbulent kinetic energy discretization and the turbulent dissipation rate discretization are using first order upwind method.

To simulate the flows over the flying wing, reviewing the high turbulent vortex produced by the NS-DBD plasma actuators, the RNG k-epsilon turbulent model is chosen. Because comparing with other turbulent models, the RNG k-epsilon turbulent model adds an additional item in the $\varepsilon$ equation, which makes the precision higher on simulating the large velocity gradient flow field. And because of considering the rotation effect, the accuracy of this model on the strong rotational flow simulation is improved.

3.3. Adaptive time step method

Discharge time of NS-DBD plasma actuators is too short (250 ns) that compares with one actuation cycle (approximate 0.014 s, actuation frequency is 70 Hz). In order to improve the computational efficiency, the adaptive time step method is adopted: in one actuation cycle, when $t < 10^{-4}$ s, $\Delta t = 5 \times 10^{-8}$ s; when $t > 10^{-4}$ s, $\Delta t = 1 \times 10^{-4}$ s. When the simulating time (in one actuation cycle) is approaching $10^{-4}$ s, time step $(\Delta t = 10^{-7}$ s, $10^{-6}$ s, $10^{-5}$ s) transits gradually from $10^{-8}$ to $10^{-4}$ s. When the simulating time (in one actuation cycle) is approaching to the end of the actuation cycle, time step transits gradually from $10^{-4}$ to $10^{-8}$ s as well. Seven pulse actuations are simulated at each attack angle and the total time $t = 0.1$ s.

Because the time step size $(\Delta t = 5 \times 10^{-8}$ s) is very small, change detection of the fluctuated aerodynamic forces is easy. As shown in figure 9, after being actuated, the aerodynamic parameters of the flying wing change very violent. But soon, the aerodynamic parameters tend to be stable. Before the start of the next pulse, aerodynamic parameter is floating up and down, but this change is very small.

4. Results and discussion

4.1. Flow separation control by NS-DBD

The aerodynamic datum, with and without the actuation, are shown in figures 10–12. EFD lines stand for experimental results and CFD lines stand for numerical results. Figures 10 and 12 show that the actuated effect is not obvious at small attack angles ($\alpha < 16^\circ$), however, the NS-DBD plasma actuators have better control effects at large attack angles ($\alpha \geq 16^\circ$). Therefore, four attack angles ($18^\circ$, $20^\circ$, $22^\circ$ and $24^\circ$) are selected for actuated dynamic numerical simulation.

Because the numerical simulation does not take the influence of the wind tunnel flow turbulence and the model surface roughness into account, there may be a kind of differences between the experiment results and the numerical simulation results. As shown in figures 10–12, the aerodynamic datum results (with and without the actuation) deviations are very small compared with numerical simulation results and experimental results.

It can be seen from figure 10 that when the actuation is applied, the actuation effect is not obvious in linear segment (small attack angles) because the vortices breakup and flying wing separation does not happen. In $\alpha = 12^\circ$–$16^\circ$, the lift
coefficient starts to increase resulting from that the NS-DBD plasma actuators control the separation from the outside wing, as shown in figure 10(a). With the attack angle increasing, the effect of actuator is gradually reflected. After the attack angle $\alpha > 16^\circ$, the NS-DBD plasma actuators control effect is obvious. In $\alpha = 26^\circ$, the maximum lift increment is 18.68%. As shown in figure 10(b), the induced drag, caused by the leading edge vortices, is increased along with the attack angle and lift increasing.

It can be seen in figure 5 that the NS-DBD plasma actuators are arranged on the right leading edge. In medium and small attack angles ($\alpha < 16^\circ$), the outside wing flow separation is controlled by NS-DBD plasma actuators results in the lift increased. However, in the case of large attack angles ($\alpha > 16^\circ$), subject to the power supply and the length of the NS-DBD plasma actuators, energy per unit length of NS-DBD plasma actuators (W m$^{-1}$) becomes less which results in a less effective flow separation control. Overall, the lift-drag ratio of the flying wing is significantly increased after actuated, as shown in figure 11.

After the actuation is applied, the lift-drag ratio increases and tends to be stable with the increase of attack angle. Due to the change of force, the pitch moment of flying wing is increased during this process, as shown in figure 12.

<table>
<thead>
<tr>
<th>Table 1. Balance static calibration result table.</th>
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<tbody>
<tr>
<td>$X$ (kg)</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Design load</td>
</tr>
<tr>
<td>Accuracy (%)</td>
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<tr>
<td>Precision (%)</td>
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</tbody>
</table>
4.2. Topological structures

Surface topological structures (leeward side, instantaneous flow field) of the flying wing including uncontrolled case (port wing) and controlled case (starboard wing, after 7 plasma actuated pulses) are shown in figure 13, in which the attack angles are from 18° to 24°.

Before the actuation is applied, a large leading edge vortex is formed on the inboard wing where the flow separates. And then the vortex reattaches at the centerline of the flying wing. Affected by the frontal concentrated vortex, the separated flow reattaches at the trailing edge and reverses on the outward wing. Subsequently, the flow separates again. With the attack angle increasing, the surface trace of the vortex becomes more divergent and the separation zone becomes larger.

After the actuation is applied, the spiral node moves upstream and to the outward wing which results from the enhanced vortex. In the meanwhile, the separation line moves towards to the leading edge. These indicate the separation zone is decreased in size and the shed leading edge vortex and the flow separation at large attack angle are inhibited.

4.3. Spatial vortex structure

Figure 14 is the streamline at section $\alpha = 20^\circ$, for the left part and right part are NS-DBD plasma actuators off and on, respectively. Due to the flying wing in stalling, the flow field is separated from the leading edge and the reattachment location is not visible as shown in the left of figure 14. And the leading edge vortex has broken down.

After being actuated, NS-DBD plasma actuators produce a strong effect on the breakup vortex. The intensity of the breakup vortex is enhanced and the structure of it is changed to be concentrated. Comparing figure 14, the zone of the separation becomes smaller and the reattachment location above the surface moves outboard.

After the actuation of the NS-DBD plasma actuators, an unsteady disturbance is imposed onto the discharge position, and the energy is injected into the shear layer. Then a spanwise vortex is formed which promotes the outer and inner of the shear layer flow to mix and changes the flow field. To a certain extent, this restrains the flow separation which achieves the effect of active flow control.

4.4. NS-DBD plasma actuators control principle

In the process of NS-DBD plasma actuators actuation, a series of blast wave and volumetric heat sources are generated. The blast waves have few effects on the separation flow field and the volumetric heat sources have the main effect [22].

Figure 15 shows the flying wing surface vorticities isolines at 5 μs, 200 μs, 0.005 s and the end of the actuation period in an actuation cycle.

After the actuation is applied, the actuation produced by NS-DBD plasma actuators (main of volumetric heat sources) propagates downstream along the surface of the flying wing while the influenced area is enlarged gradually. The volumetric heat sources generated by each actuation change the flow field of the flying wing gradually, which changes the local temperature and density and induces several vortex structures. The vortex structures entrain the outer high-momentum fluid into the shear layer, thereby strengthening the mixing of the shear layer with the main flow and delaying separation or even reattaching a separated flow.

The velocity contours of $\alpha = 0.5, 0.7, 0.9$ at $\alpha = 20^\circ$ are shown in figure 16. The structure and intensity of the breakup vortices of the flying wing have been changed obviously after NS-DBD plasma actuators actuated at large attack angles. The breakup vortices become concentrated and the separation zone is reduced correspondingly as well which results in the lift-to-drag and pitch moment of the flying wing increase.

5. Conclusion

NS-DBD plasma actuators applied on the flying wing so as to control the separation flow is investigated in this paper. Through comparison results between experiment and numerical simulation method, the nanosecond pulse plasma aerodynamic actuation mechanism and the coupling effect of plasma actuators and flow field are revealed. The main conclusions are as follows:

1. NS-DBD plasma actuators have an effective control for flying wing separation flow. Their aerodynamic actuation
can change the lift-drag characteristics and improve the lift-to-drag ratio of the flying wing. They inhibit the vortices separation obviously at large attack angles. After actuating, the aerodynamic forces and torques of the flying wing are increased. The maximum lift increment is 18.68%.

2. After actuating, volumetric heat produced by NS-DBD plasma actuators spread downstream along with the wind flow, which impacts the temperature gradient of the flow field and changes the flow field structures. At the same time, NS-DBD plasma actuators generate the cross flow vortices, which promotes the outer flow field to mix with the inner flow field in the shear layer and inhibits the flow separation.

3. After actuating, NS-DBD plasma actuators significantly change the structures and intensities of the vortices. The breakup vortices become concentrated and the vortex center moves to the outside wing. Spiral node has the upstream and outside wing direction movement. The separation zone is decreased accordingly.

NS-DBD plasma actuators have a certain effect on controlling the flying wing flow, especially at large attack angles. This paper study results provide a reference for other structure NS-DBD plasma actuators flow control.

In the future study, more efficient NS-DBD plasma actuators need to be developed to improve the capability of its aerodynamic actuation and to realize the higher velocity active flow control.
Figure 13. Topological structures on the leeward side with uncontrolled case (port wing) and controlled case (starboard wing).

Figure 14. Streamline at $\alpha = 20^\circ$ for the actuator off/on case at $x/C = 0.4, 0.6, 0.8$. 
Acknowledgments

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Figure 15. Flying wing surface vorticities isolines in an actuation cycle.

Figure 16. The velocity transformation contours of \( x/C = 0.5, 0.7, 0.9 \) at \( \alpha = 20^\circ \).
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