Flow Separation Control over a NACA 0015 with AC and Nanosecond Pulse Driven DBD Plasma Actuators.

A. Debien, N. Benard, E. Moreau.

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Useful plasma for aerodynamic control - demonstrate how surface & spark discharge plasma actuators could be used to control aircraft aerodynamic flow.

Mean velocity field produced by DBD actuator (20 kV, 1 kHz), side view.
Plasmaero

- demonstrate how surface & spark discharge plasma actuators could be used to control aircraft aerodynamic flow.

Time resolved velocity (black) induced by DBD actuator.

Time resolved velocity (blue) induced by DBD actuator with burst modulation.
- demonstrate how surface & spark discharge plasma actuators could be used to control aircraft aerodynamic flow.

✓ time-resolved EHD force evaluation by PIV measurement
✓ multi-DBD plasma actuators development
✓ control of trailing edge separation
✓ control of middle-chord separation

Velocity profile versus x at y = 1 mm (where maximal velocity is observed).
Experiments Facilities

- Test section (P’ – ENSMA): 2.4 X 2.6 m², $U_\infty \leq 60$ m/s, turbulence level $\leq 0.5\%$
- NACA 0015 airfoil: 0.5 m-Chord, 1.2 m-Span
- PIV: 2 x JAI 12-bit cameras (Pulnix, RM-4200CL, 2048x2048 pixels², pixel size 179 µm)
- 7 instationary pressure sensors (Kulite XCQ-080-2PSID, 4 kHz)
Multi-DBD actuation
Experimental setup:

- Multi-DBD composed of three DBD between x/c 18 and 36% (upstream the separation)
- Electric wind produced in the downstream direction
- $U_\infty = 40$ m/s, $Re = 1.3 \times 10^6$, tripped ($x/c = 0.4\%$)
Experimental measurements:

<table>
<thead>
<tr>
<th></th>
<th>U_∞ = 40 m/s, Re = 1.3 \times 10^6</th>
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<tbody>
<tr>
<td><strong>MDBD</strong></td>
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<tr>
<td></td>
<td>V (kV)</td>
</tr>
<tr>
<td></td>
<td>F_{ac} (Hz)</td>
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<td></td>
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<td></td>
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</tr>
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<td>V (kV)</td>
<td>12-20</td>
</tr>
<tr>
<td></td>
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<tr>
<td>F_ac (Hz)</td>
<td>1 k</td>
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<tr>
<td></td>
<td>50 - 1 k</td>
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<tr>
<td>F_burst (Hz)</td>
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<tr>
<td></td>
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![Burst period chart](chart.png)
**Amplitude voltage impact:**

$M_{dbd}, f = 1 \text{ kHz}, Re = 1,3 \times 10^6, U_{DBD} = 3 – 6 \text{ m/s}, P_{elec} = 0.3 – 1.9 \text{ W/cm}$

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Driven frequency impact:

**Mdbd, V = 20 kV, Re = 1,3 \times 10^6**

Influence of driven frequency on electric wind production (V = 14 kV). Pons et al. 2005

- two optimal frequencies:
  - 50 Hz (low velocity production)
  - 500 Hz
Burst modulation
**Burst modulation:**

- combine velocity production due to $f_{ac}$ with low frequency induced by burst modulation

- optimal frequency:
  - √ 50 Hz

**Time resolved velocity (blue) induced by DBD actuator with burst modulation.**
Nanosecond Pulse DBD
Nanosecond Pulse DBD

Experimental setup:

Sketch of nanosecond discharge

Current and voltage versus time

Positive pulse (10 kV, $t_{\text{rise}}=50$ ns, pulse width 200 ns, $f_p=5$ Hz, Energy = 0.2 mJ/cm per pulse) 10 μs/image (shadowgraphy)
Nanosecond Pulse DBD

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Leading edge separation

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<td>2.1 k</td>
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<td>F_burst (Hz)</td>
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<td>26 - 798</td>
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$U_\infty = 40 \text{ m/s, } Re = 1.3 \times 10^6$
Leading edge separation

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\(U_\infty = 40\) m/s, \(Re = 1.3 \times 10^6\)

\(\alpha = 13.5^\circ\)

\(x/c = 1\%\)

\(x/c \# 43\%\)

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09/12/2011
**Pulse frequency impact:** \( ns \text{ DBD, } V = 9 \text{ kV, } Re = 1.3 \times 10^6, \alpha = 13.5^\circ \)

- recirculation decrease as \( f_{\text{pulse}} \) increase.

![Diagram showing pulse period and voltage over time with recirculation decrease as pulse frequency increases.]

\( F_p = 1632 \text{ Hz ( } F^* = 11.4) \)
Burst modulation
Burst modulation:

- optimal frequencies between 60 and 100 Hz

ns DBD, $F_{\text{pulse}} = 1632$ Hz, $V = 9$ kV, $Re = 1,3 \times 10^6$, $\alpha = 13.5^\circ$

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09/12/2011
ac – ns pulse comparison

- $U = 40 \text{ m/s}$, $Re = 1.3 \times 10^6$, $\alpha = 11.5^\circ$, tripped
- Multi-DBD: $V = 20 \text{ kV}$
- ns DBD: $V = 9 \text{ kV}$
Conclusion

- **Multi-DBD:**
  - Both pulse and driven frequency appear to be important in separation control ($F^+ = 0.3$)
  - Best separation delay has been obtained with continue actuation

- **nanosecond DBD:**
  - able to reattach a flow that naturally detaches at 43% for $Re = 1.3 \times 10^6$
  - Flow sensitive to nanosecond DBD burst modulation with optimum between $0.5 < F^+ < #1(0.91)$
Thank you for your attention
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