Active Flow Control by Using Plasma Actuators

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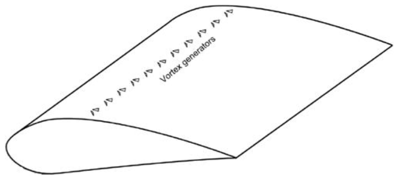
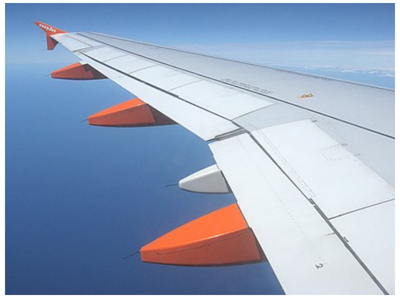
Introduction

- Aerodynamic flow control techniques can be divided into passive, mechanical and active flow control
- Passive flow control methods do not require any external energy sources; examples include geometric shaping and vortex generators
- Mechanical flow control methods, sometimes considered a form of active flow control, modify the air flow by moving parts of the wing; examples include ailerons and flaps
- Active flow control methods (excluding mechanical) directly require external energy input and often a control loop to directly modify the flow field without any moving parts; examples include synthetic jets and plasma actuators
- Today, the vast majority of flow control methods are either passive or mechanical flow controls, but there are several limitations with these techniques
- Plasma actuators are being researched to provide an alternative to passive & mechanical flow control

Problem statement

Existing flow control technique	Inherent disadvantages of given flow control technique
Passive flow control	▪ Passive flow control is permanent (e.g., vortex generators, airfoil cavities) and therefore cannot be selectively enabled & disabled as flight conditions change ▪ Compromises are often made for aircraft performance in different areas of the flight envelope, most commonly between slow and high speed flight
Mechanical flow control	▪ Mechanical flow control techniques require complex moving parts and mechanisms (e.g., ailerons and flaps), which add cost, complexity and structural limitations to the aircraft ▪ For example, flaps typically require external track mechanisms which are kept in bulky fairings, adding drag to the aircraft even when not in use

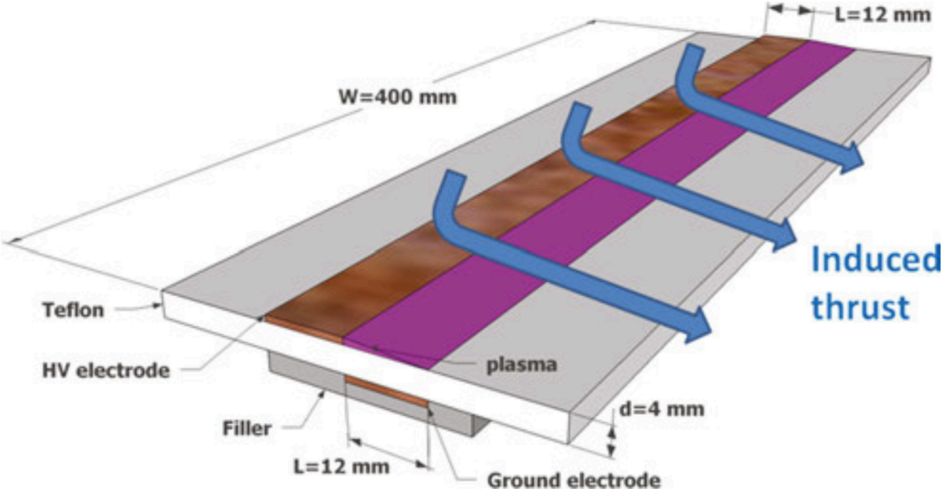


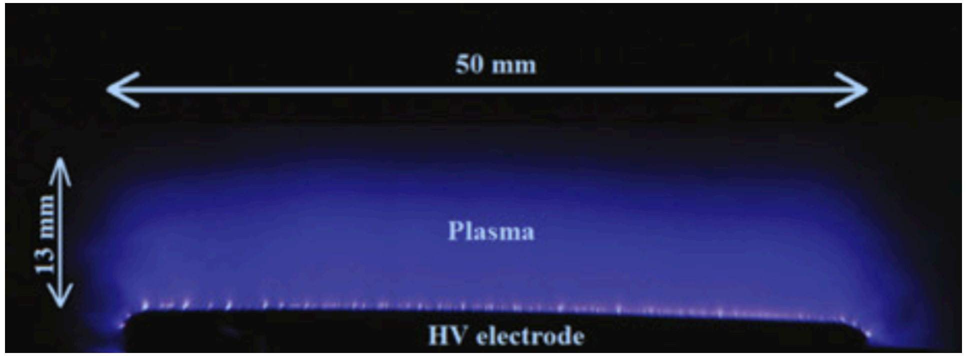


Plasma actuators are being researched as a potential alternative active flow control technique to overcome these limitations and disadvantages of existing commonly-used flow control techniques

Basic principles of plasma surface dielectric barrier discharge (DBD) aerodynamic actuators

- Plasma actuators are based on the ‘ionic wind’ principle of electrohydronamic interaction. High electric fields can locally ionize the air. The produced heavy-charged species are accelerated by the applied electric field and, by means of collisions, accelerate the surrounding neutral gas
- On the surface of the airfoil, there is a pair of electrodes separated by a dielectric (insulating) material
- A sinusoidal voltage in the range of 5–50 kV and frequency of between 1 and 100 kHz ignites a plasma topology at the surface, creating a surface discharge
- The surface discharge produced by these devices tangentially accelerates the flow field due to the electrohydroynamic interaction
- This can produce boundary layer modifications with induced speeds up to 10 m/s
- The dielectric material prevents the creation of an arc between the two electrodes; DBD actuators typically generate non-thermal plasmas, reducing power consumption and allowing their use over heat sensitive surfaces

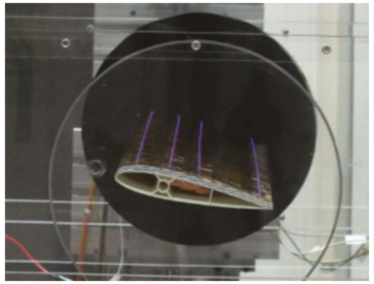


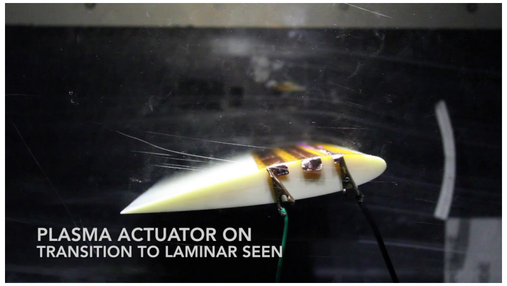


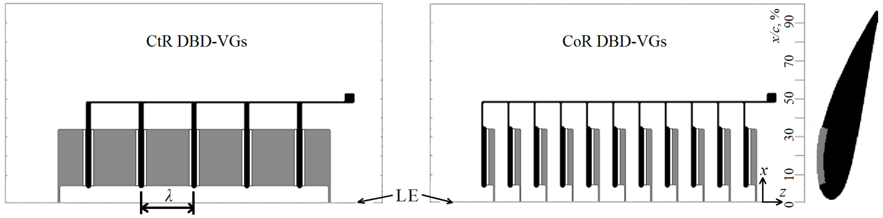
There are several possible configurations for mounting plasma actuators

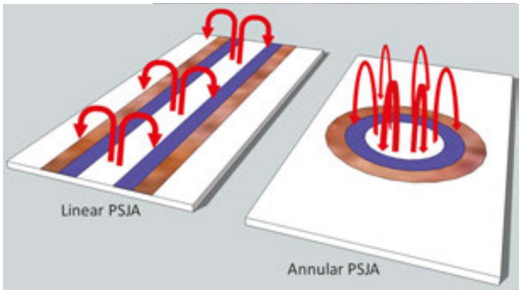
Deep-dive to follow

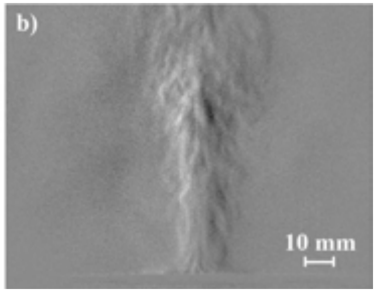
Configuration	Description
1 Span-wise actuator	▪ The plasma actuator is mounted along the span of the wing, either as a single or multiple actuators
2 Chord-wise actuator	▪ The plasma actuator is mount along the chord of the wing, with potentially multiple sets of actuators
Synthetic jet configurations	▪ Multiple actuators are used in combination to create flow perpendicular to surface of the airfoil





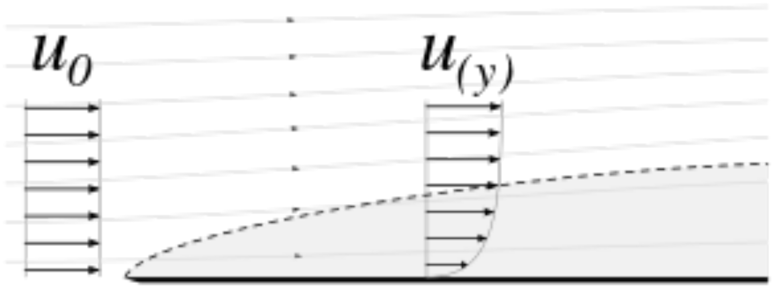






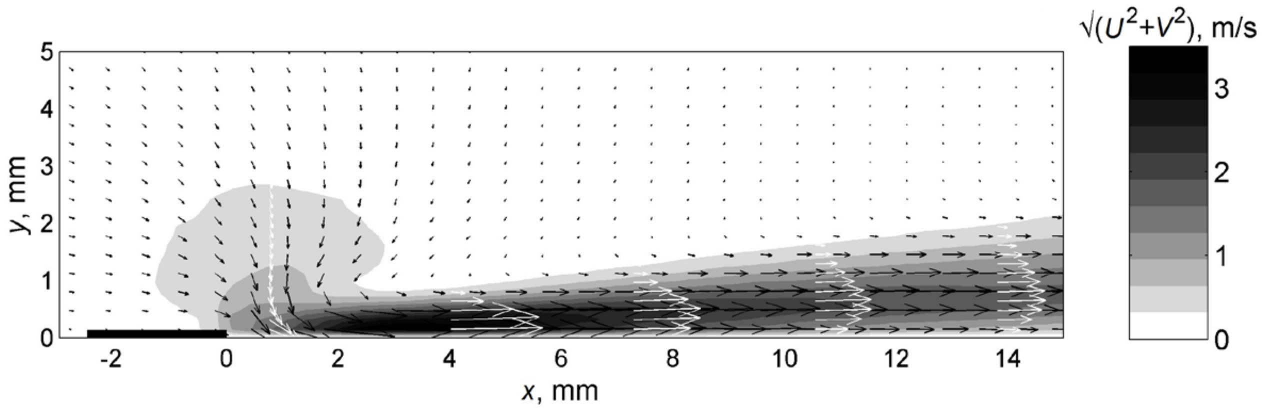
1 DBD actuators accelerate the fluid in the boundary layer of the flow field

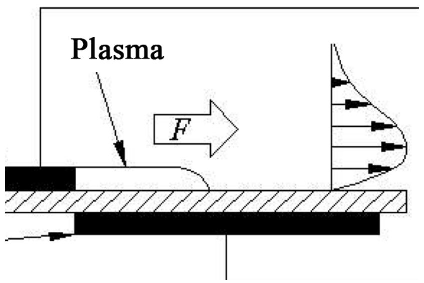
Without plasma actuators



- In boundary layer, velocity is slower near surface due to viscous forces between surface and fluid
- Flow velocity varies from zero at the surface to freestream velocity
- Boundary layer flow can be laminar or turbulent

Addition of DBD plasma actuators

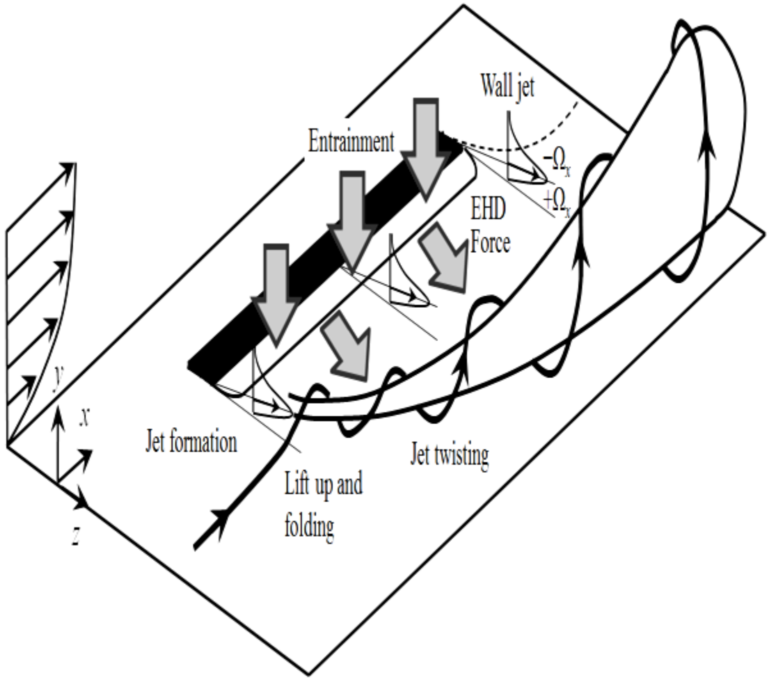




- Plasma actuator accelerates the fluid in the boundary layer
- This changes the profile of the fluid velocity, with the fluid near the surface flowing faster than without the plasma actuator

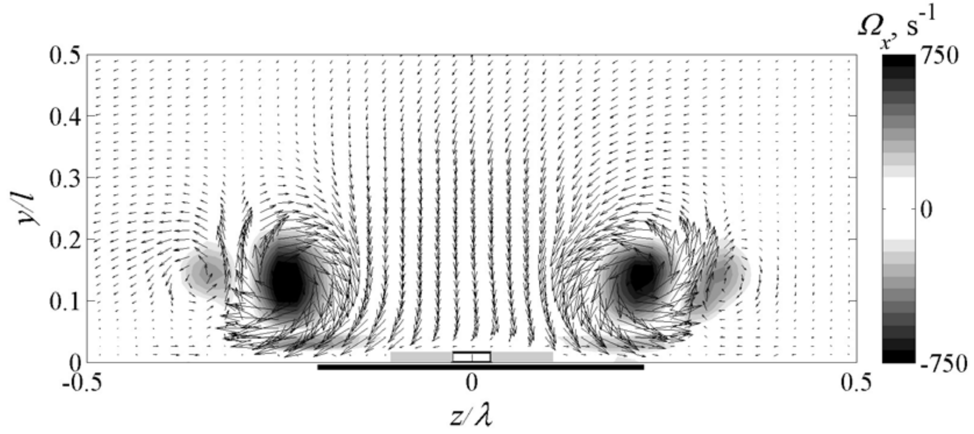
2 Chord-wise DBD actuators generate vortices

Chord-wise DBD actuators create a vortex in the boundary layer

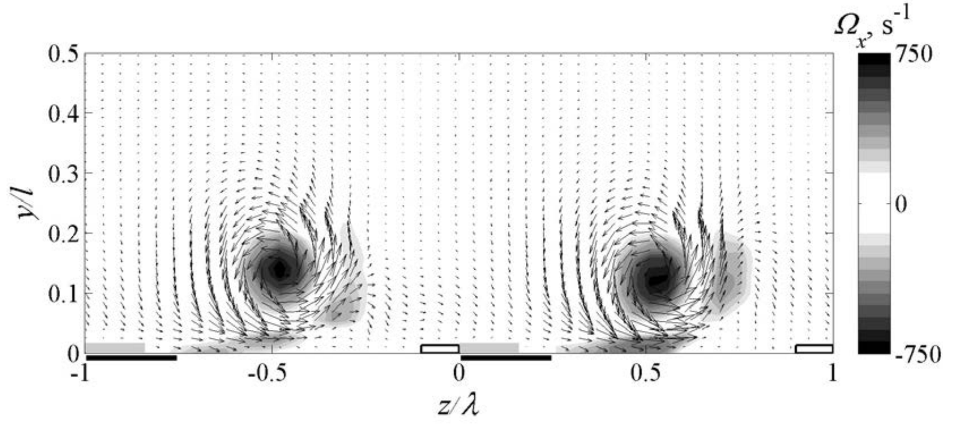


Different arrangements of chord-wise DBD actuators can be used to create different vortex patterns

Example: two vortices, opposite directions



Example: two vortices, same directions



Deep-dive to follow

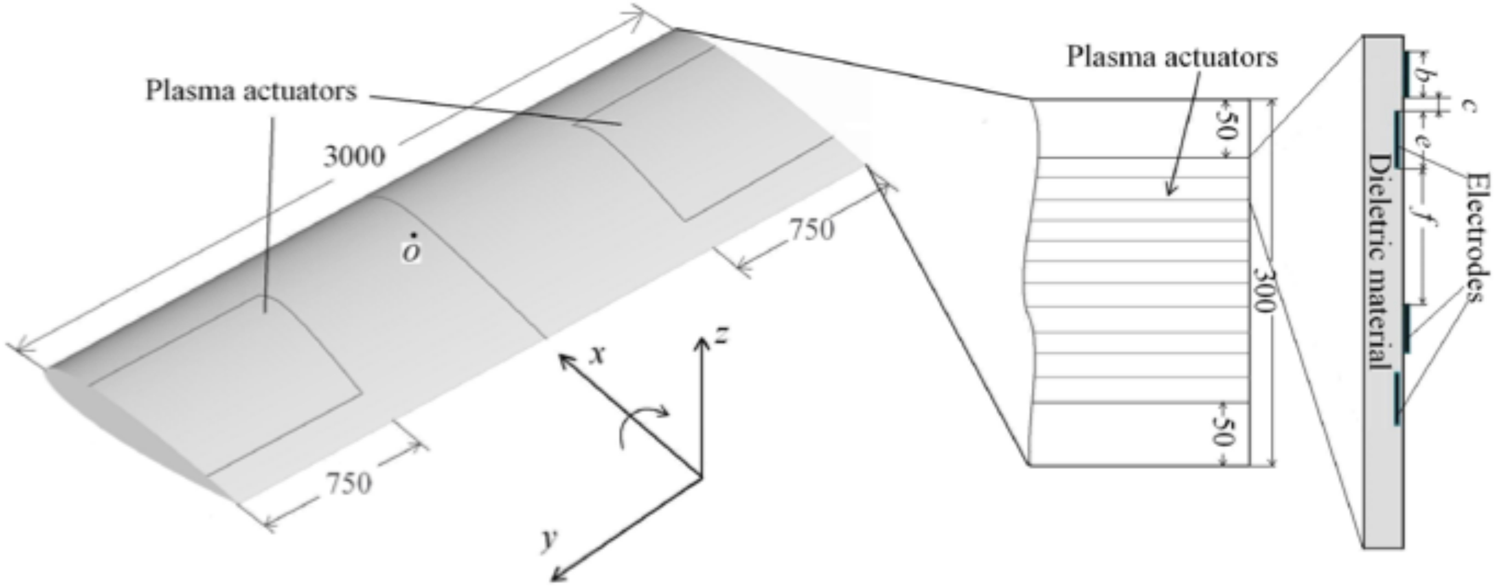
Potential applications of plasma actuators

1 Flight control	▪ Plasma actuators can be used as an alternative to ailerons, elevator and rudder control surfaces to control the flight of the aircraft
2 Flaps	▪ Plasma actuators can be used as a on-demand high lift device, similar to flaps ▪ Can be activated & de-activated instantly, unlike mechanical flaps
3 Improve airfoil performance using vortices	▪ Chord-wise plasma actuators can be used to generate vortices and improve airfoil performance ▪ Unlike traditional vortex generators, these can be turned on and off or their strength adjusted
4 Stall control	▪ Span-wise plasma actuators can delay the onset of a stall, to help with slow flight performance
Tip clearance seals in turbines	▪ In turbines (e.g., jet or gas turbines), there needs to be a clearance between the tips of the blades and the enclosing surface. Plasma actuators can be used to reduce 'leakeage' around this blade tip
Active noise reduction	▪ Adoption of plasma actuators over landing gear and trailing edges can modify the flow pattern such that noise is reduced, potentially permitting flight in noise sensitive areas (e.g., night landings near cities)
Supersonic & hypersonic flow	▪ Plasma would be easier to generate due to the low atmospheric pressure and high surface temperature of hypersonic aircraft. The low atmospheric pressure, an advantage for plasma actuators, hinders classic aerodynamic surfaces and thus they provide little control & actuation

1 Use case: flight control

Plasma actuators can replace control surfaces to provide directional control of the aircraft around all three axis

Example configuration of plasma actuators to replace ailerons

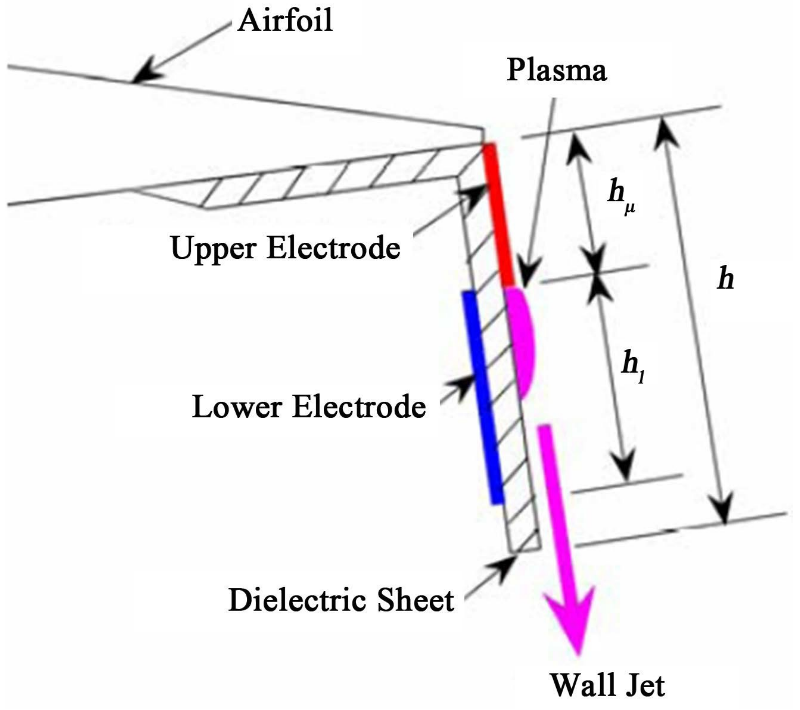


Key benefits

- No moving surfaces, simplifying the structural design of the aircraft wing and potentially reducing drag
- No moving surfaces, enabling advanced wing designs which would otherwise not be possible (e.g., micro size)
- Advanced flight control: the flow around each section of the aircraft wing can be controlled separately, allowing a larger flight dynamic envelope and increased efficiency
- Easy mixing of control surfaces, such as for flaperons

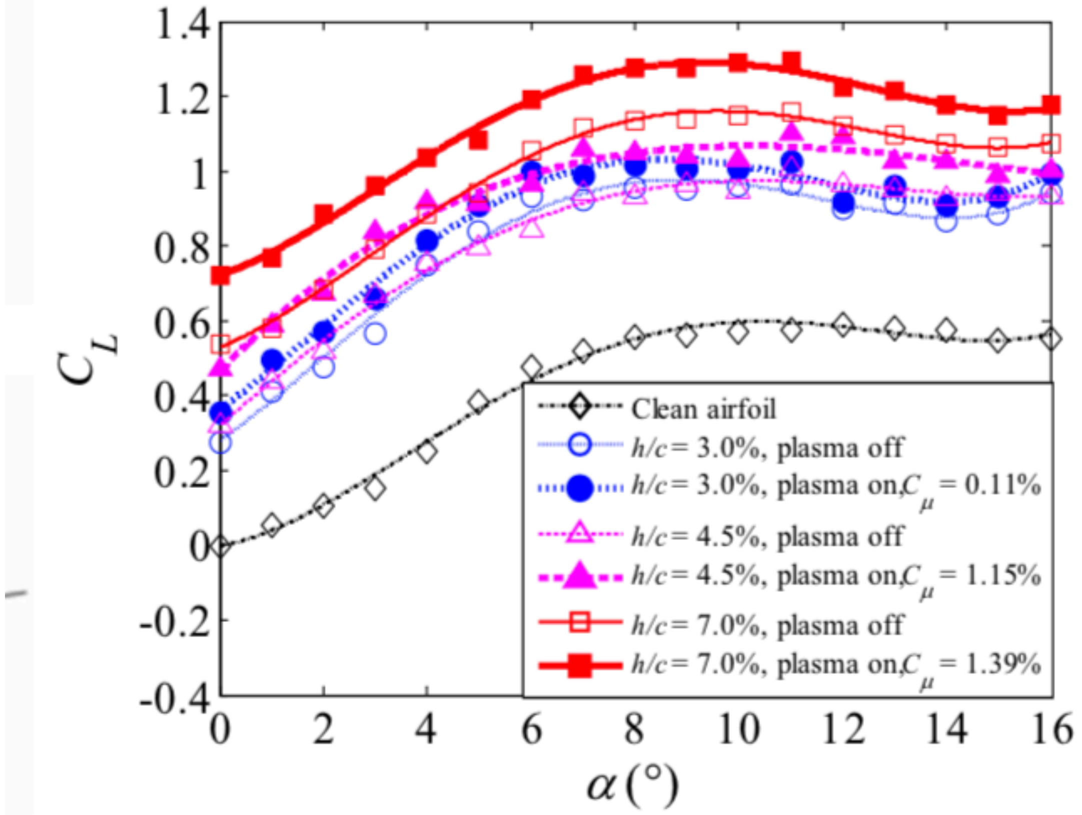
2a Use case: enhancing effect of gurney flaps

A single plasma actuator can be mounted on the gurney flap to create a wall jet



The strength of the wall jet due to the plasma actuator can be adjusted as needed depending on the flight conditions

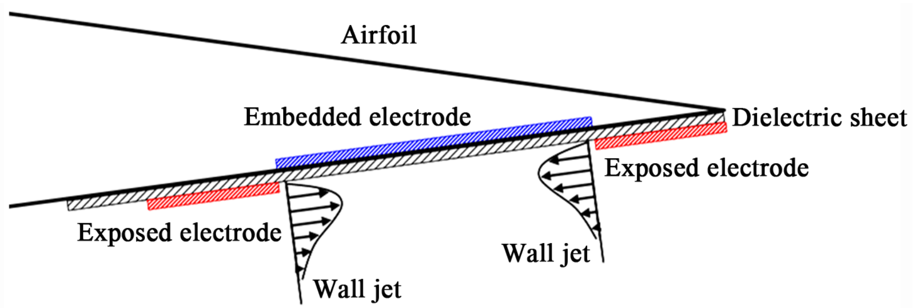
The addition of this plasma actuator to the gurney flap increases its coefficient of lift by up to 39%

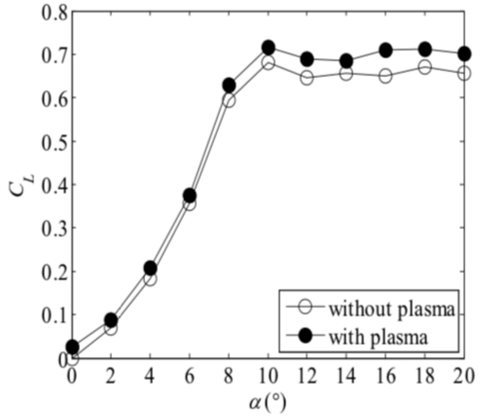


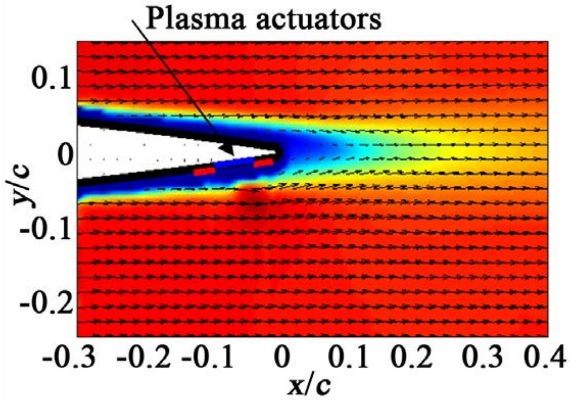
2b Use case: standalone high-lift devices

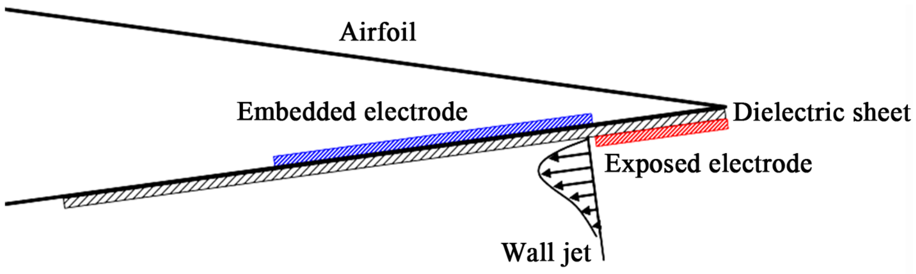
Plasma actuators can also be used to create a standalone wall jet at the trailing edge

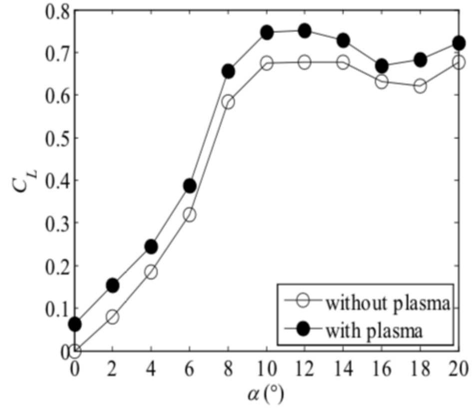
These plasma actuators mimic the effect of a gurney flap to increase the effective chord length of the airfoil

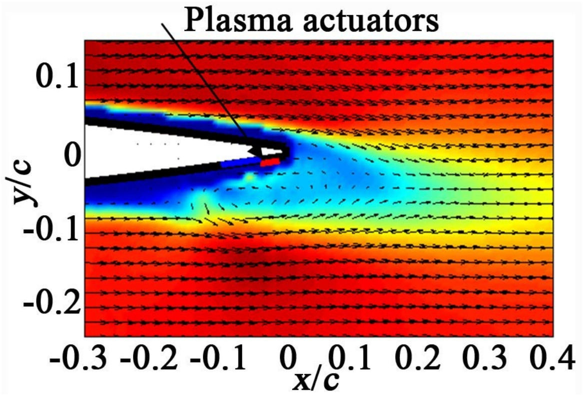










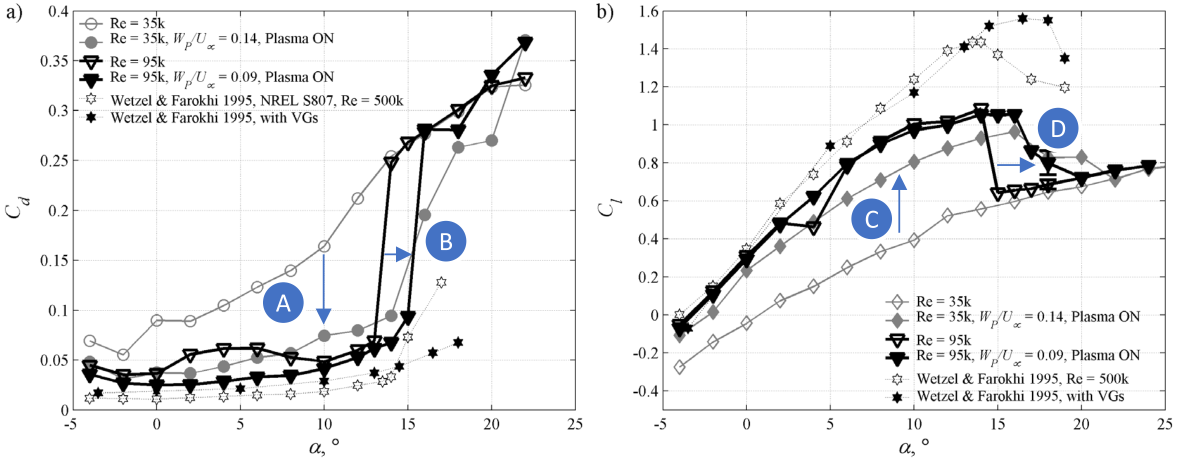


3 Use case: generate vortices to improve airfoil performance

Vortex generators are frequently used on aircraft to improve airfoil performance

- Vortex generators are placed on the upper surface of the airfoil, near the leading edge, to create vortices
- The vortices generate a turbulent boundary layer and energize the stagnant boundary layer
- This energized boundary layer is more resistant to flow separation, delaying the stall onset and increasing lift
- These generators are often used to improve slow-speed flight and increase MTOW, especially in aircraft limited by their stall speed and climb performance

Plasma actuators can also generate vortices to improve airfoil performance



A At very low Re numbers (Re=35k), there is a significant reduction (~50%) of drag from the airfoil

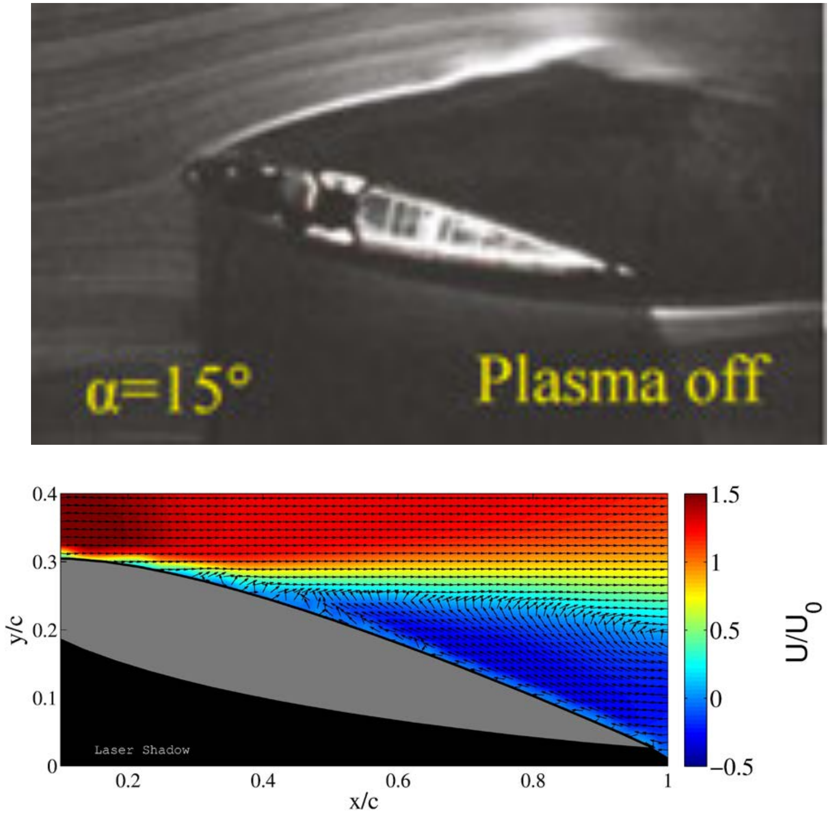
B There is also an increase in the stall angle, and the sharp increase in drag associated with it

C At very low Re numbers (Re=35k), there is a significant increase (~75%) in lift from the airfoil

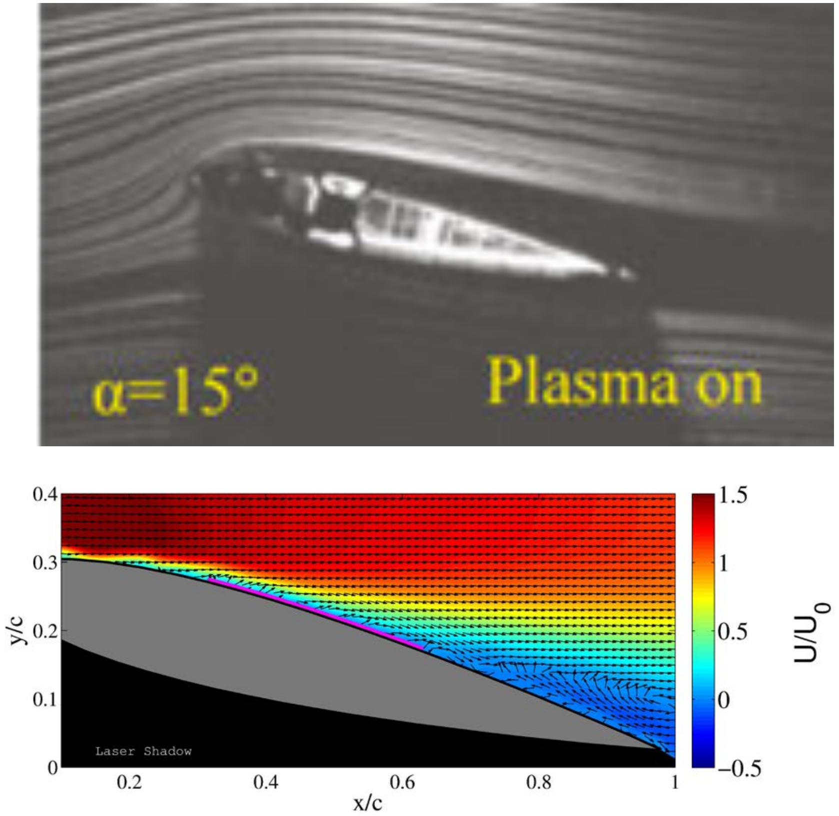
D Here we also see the increase in the stall angle, and the sharp drop in lift associated with it

4 Use case: delay onset of stall

NACA 0015 without plasma actuators



Addition of DBD plasma actuators



Key takeaways

- Addition of a span-wise DBD plasma actuator increases the stall angle of the aircraft
- This can increase lift generated at slow speeds, allowing the aircraft to fly slower
- Alternatively, the aircraft can generate more lift at the same speed by increasing its angle of attack, hence potentially its MTOW can be increased

Advantages of plasma DBD actuators over classic flow control techniques

Existing flow control technique	Size of advantage	Explanation of advantage
Flexible placement	**HIGH**	▪ Plasma actuators can be integrated almost anywhere in the wing, without regard for structural integrity ▪ This enables simpler wing structures and potentially more advanced wing designs
No drag or interference when not used	**HIGH**	▪ Plasma actuators do not create any drag or interfere with the air flow when not in use, increasing efficiency over traditional flow control methods (e.g., flaps, gurney flaps) when not needed
Fast actuation times	**HIGH**	▪ Plasma actuators can be instantly turned on/off, whereas mechanical control surfaces require movement which takes time
On-demand availability	**MEDIUM**	▪ Plasma actuators can be enabled and disabled on-demand and their strength varied. By contrast, conventional flaps for typically have set positions. Likewise, for example vortex generators are mounted permanently, hence affect flow even when not needed
Low power consumption	**LOW**	▪ The paper author claims a lower power consumption, but then also states they are not efficient, but this seems seems to be contradictory as you would require a great power consumption to generate a large aerodynamic effect, hence size of advantage is low

Limitations of plasma DBD actuators and areas for potential future research

High barrier to adoption

Low max induced velocity

- The maximum induced velocity achieved by current plasma actuators has been less than 10 m/s, limiting their effectiveness in air flow with a high freestream velocity
- This seriously limits their use on aircraft of all sizes to replace traditional control surfaces and flow control devices

Low efficiency

- Plasma actuators have a low efficiency of converting electric energy to kinetic energy of the air flow
- This is not a big disadvantage for use-cases that require only occasional use (e.g., flaps for takeoff/landing), but would prevent these actuators from replacing flow control devices that are constantly being used – e.g., the elevator or trim tabs

Most effective at low Reynold's number

- The aerodynamic effects of plasma actuators are highest for airfoils with low Reynold's numbers, where viscous forces are largest (this is partly due to the fact they work in the boundary layer and partly due to the low max induced velocity)
- This inhibits their use on large-scale aircraft, but applications for micro UAVs could be more promising, especially since mechanical controls are challenging to design on micro-aircraft

Dangerous high voltages & electromagnetic noise

- Plasma actuators use high voltages and generate electromagnetic noise
- However, the dangers of high voltages are minimal with sufficient safety equipment and insulation; likewise aircraft equipment is shielded already to protect against electromagnetic noise

Lower barrier to adoption

Potential research areas

- A breakthrough in the max induced velocity of plasma actuators would be a major step towards their use in real-world aircraft
- This would most likely require researching how to improve their efficiency, if at all possible, as the energy required to increase the induced velocity is proportional to the square of the velocity
- By contrast, the dangers of high voltages and electromagnetic noise are already well understood and could be fairly easily mitigated, hence are not necessarily a major barrier to real-world use of plasma actuators

References

- "Active Flow Control by Using Plasma Actuators" by Gabriele Neretti, *InTech Recent Progress in Some Aircraft Technologies,* 2016
- "Plasma Virtual Actuators for Flow Control" by Kwing-So Choi et al., *Journal of Flow Control, Measurement & Visualization,* 2015
- "Traditional and New Types of Passive Flow Control Techniques to Pave the Way for High Maneuverability and Low Structural Weight for UAVs and MAVs" by Mustafa Serdar Genç et al., *InTech Recent Progress in Some Aircraft Technologies,* 2019
- Various sources on internet for photos & general information (e.g., Wikipedia)

Appendix

Sealing tip clearances in gas turbines