PLASMA FLYER – THE WORLD'S FIRST PLASMA FLOW CONTROLLED FLYING WING - model I

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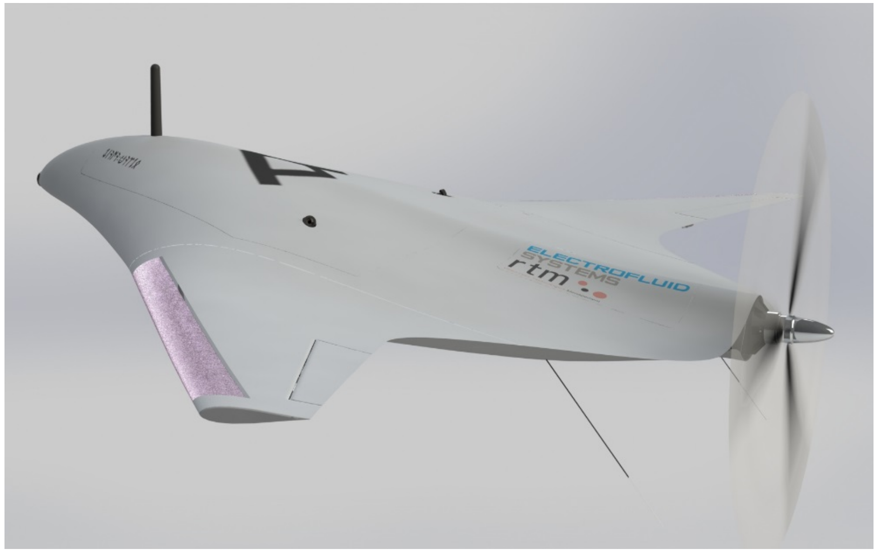
Hauptstr. 35, 76879 Bornheim



4th EASN Association International Workshop on Flight Physics & Aircraft Design
27th – 29th October 2014
RWTH Aachen University

Outline

- Motivation
- Experimental Setups
  - Flying Wing Airfoils
  - Flying Wing Half Models
  - Flying Wing Flight Models
- Discussion of Results
  - Airfoil Performance
  - Optimization Study
  - Half Wing Performance
- Conclusions and Outlook

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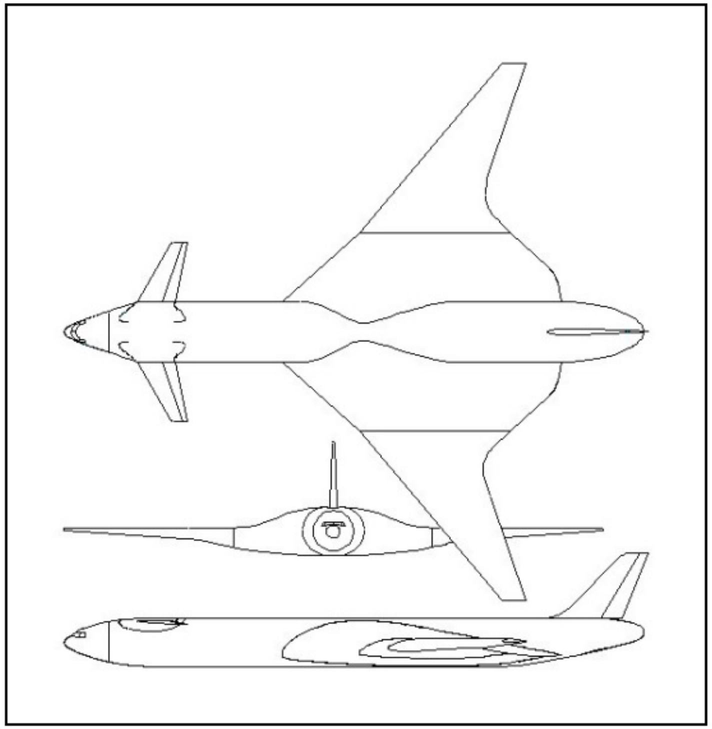
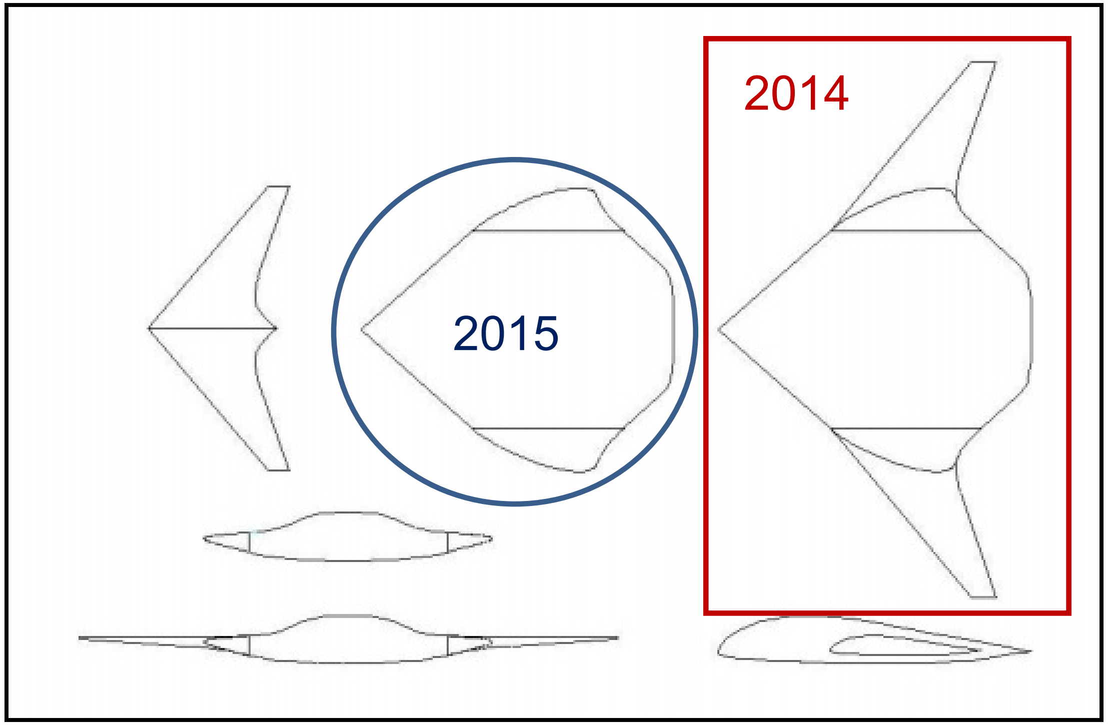
Motivation

Motivated by Blended Wing and Hybrid Configurations from 1996 to 1998





<u>Both pictures from my first publication at TU Berlin in 1998:</u>

B. Göksel (1998) Studien zu einem bionischen Megaliner zukünftiger Generation. DGLR-JT98-19, Tagungsband I, Deutscher Luft- und Raumfahrtkongress 1998, Bremen, pp. 771-785.

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Motivation

Motivated by Blended Wing and Hybrid Configurations from 1996 to 1998

Extended design study with three students was honored with a reddot design award in 2008.

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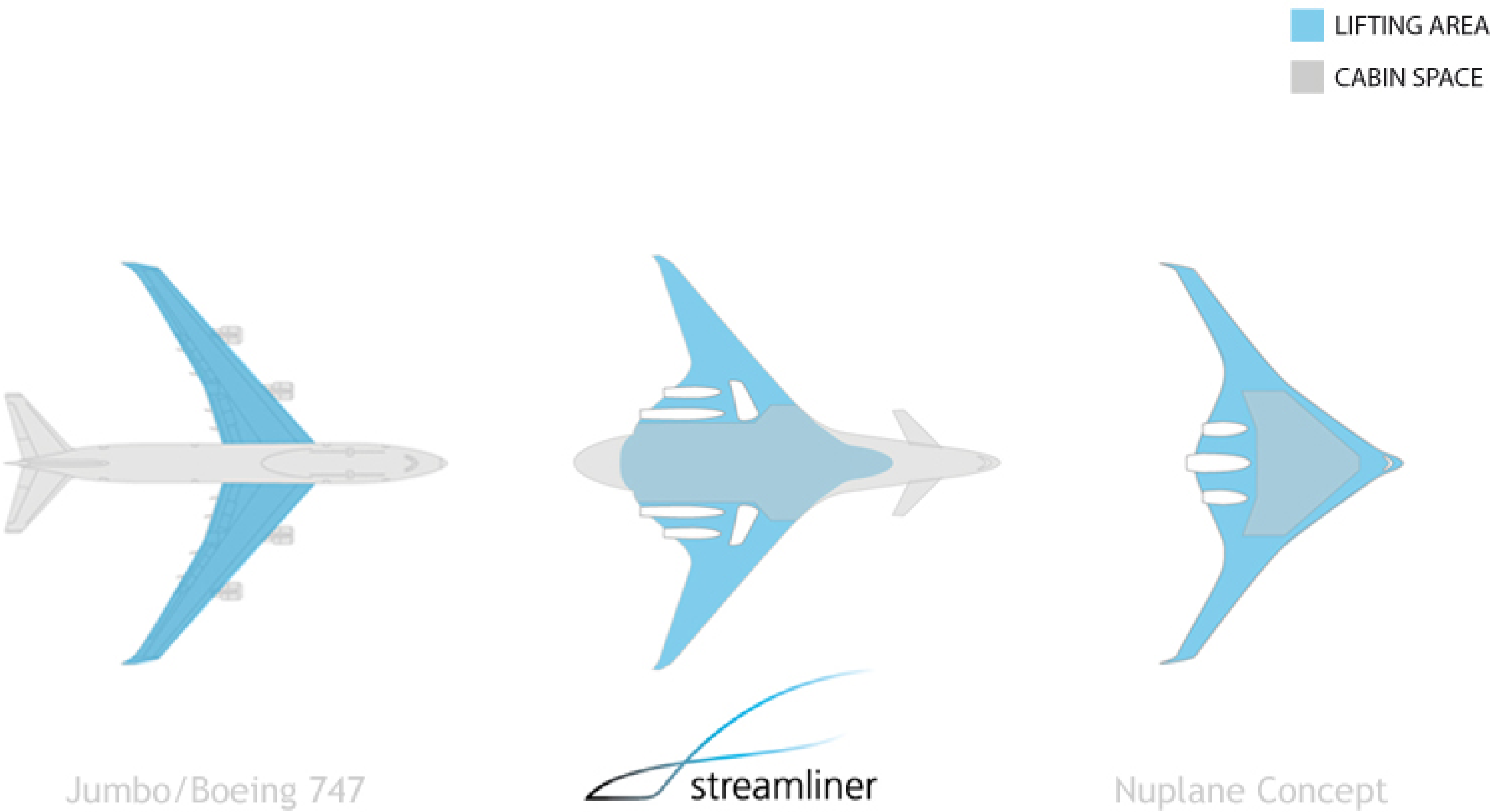

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Motivation

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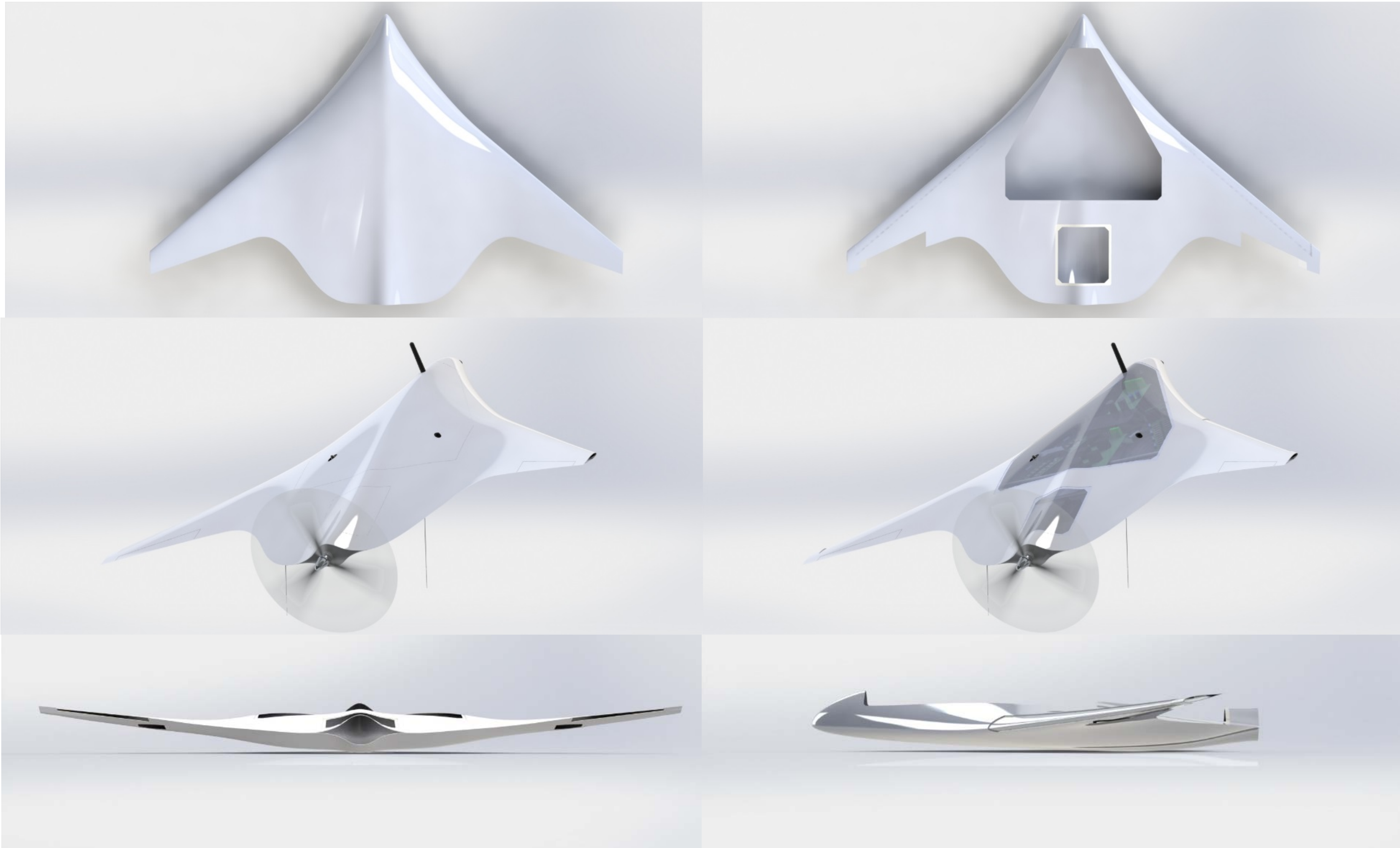

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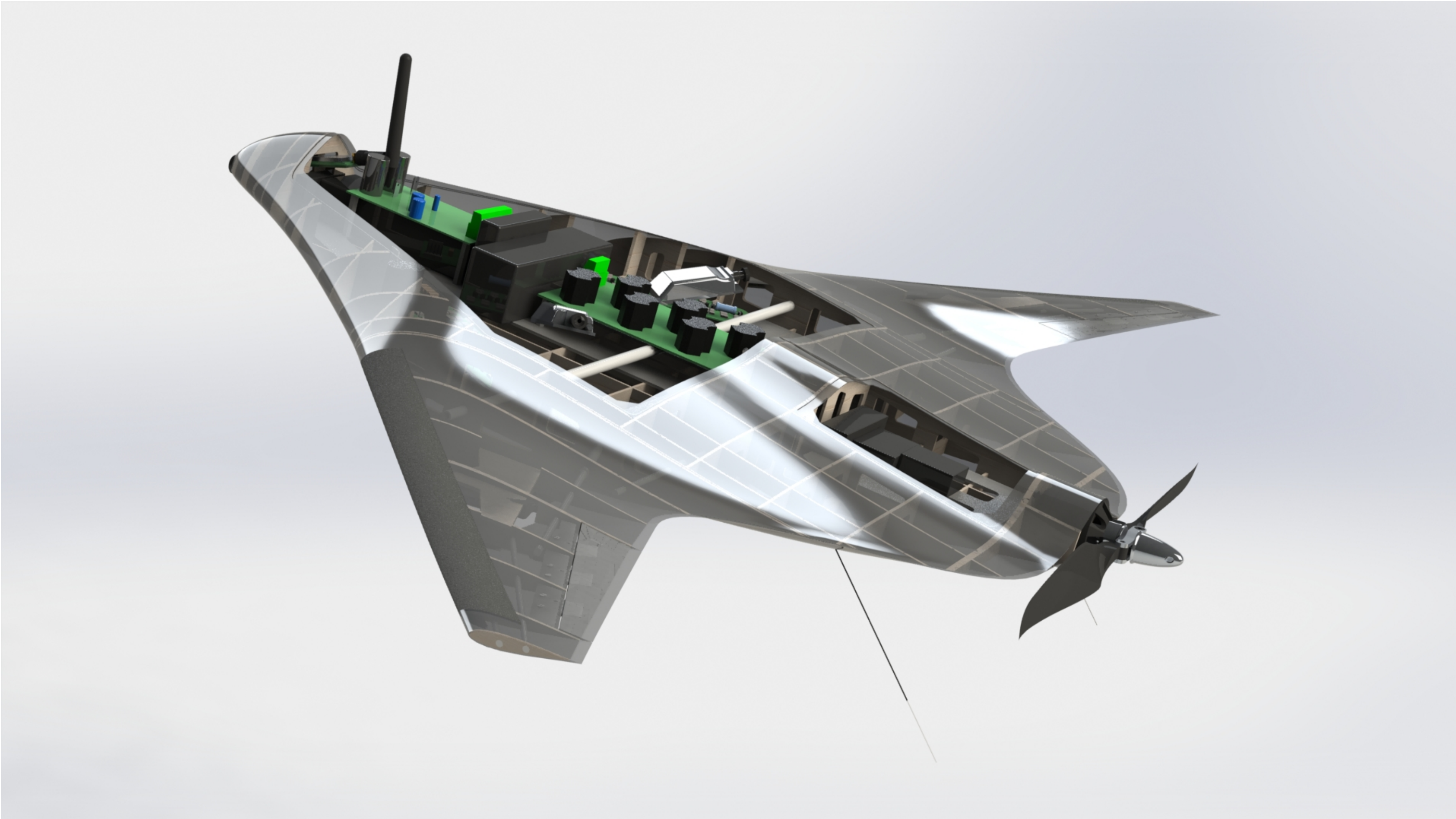

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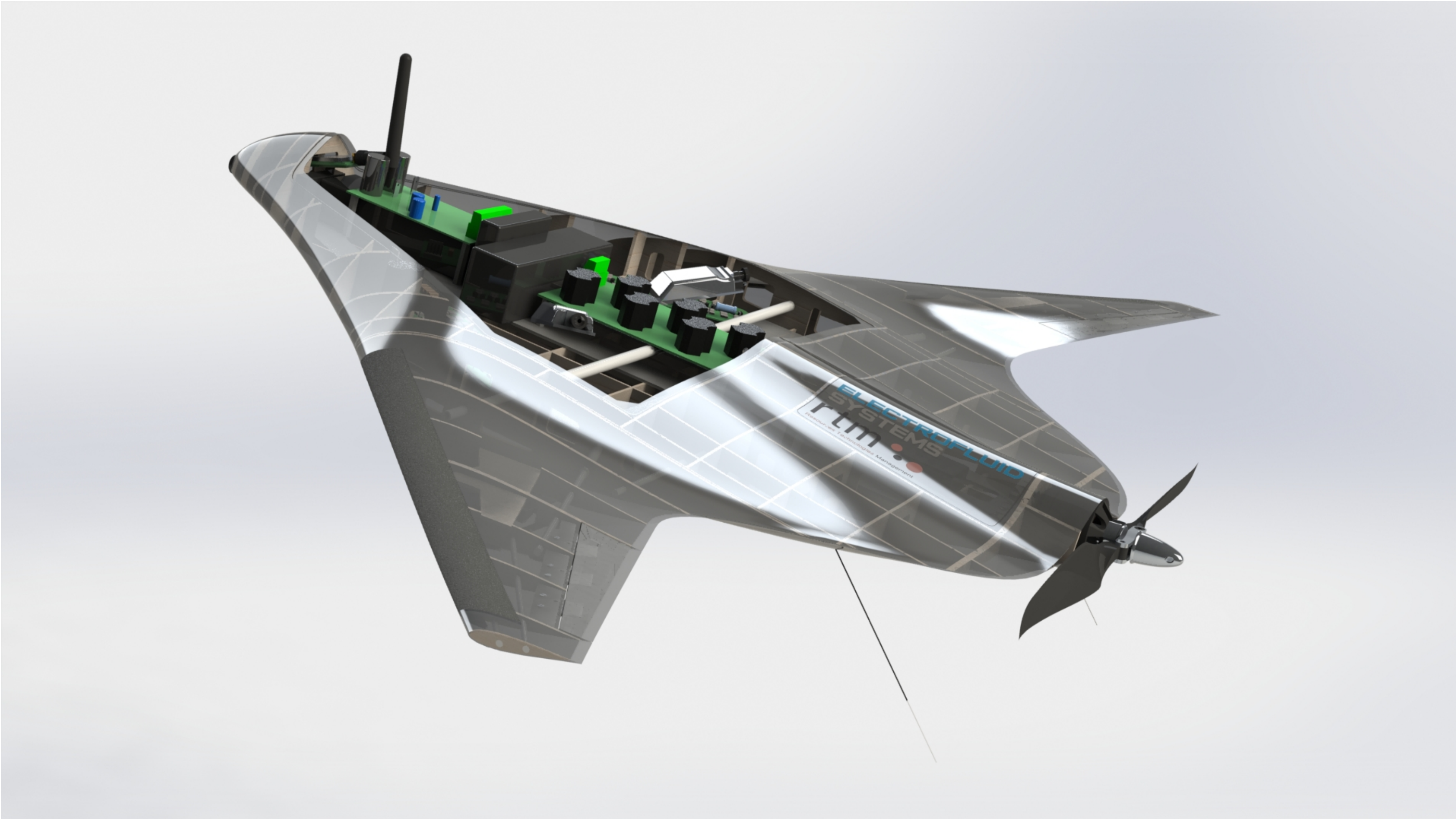

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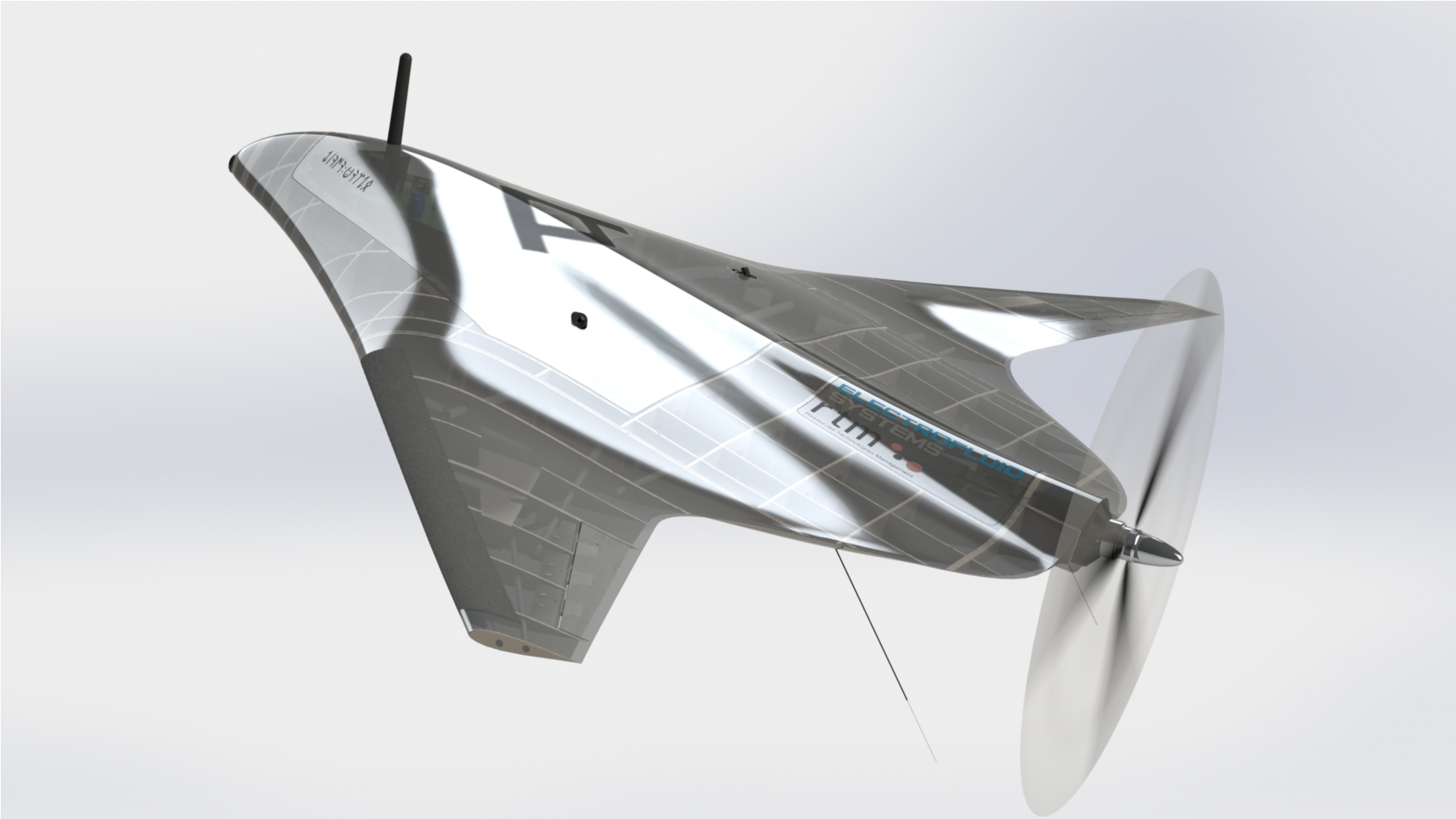

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Motivation

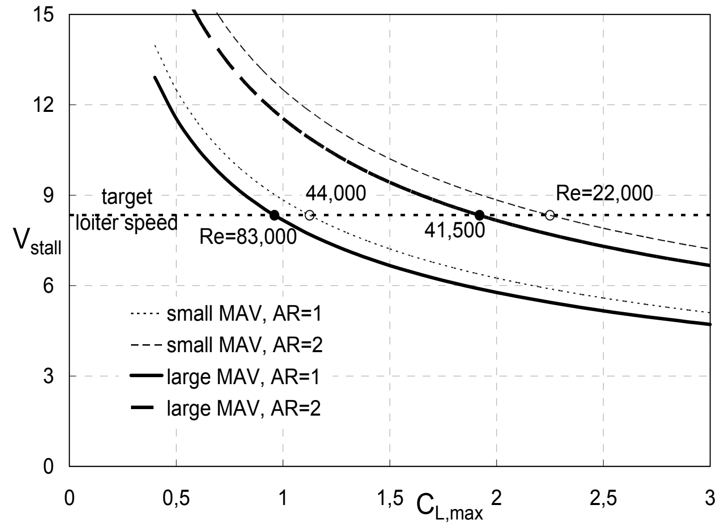
Motivation for Mini (<1.6m) and Micro UAVs (<0.8m)

Conventional Reynolds number UAVs (with Re > 200,000) achieve target loiter speeds by deploying flaps.

The generation of useful lift at Re<50,000 is particularly challenging because passive tripping of the boundary layer is virtually impossible.

Without flow control low aspect ratio MAVs would have to fly almost ballistically to avoid stall at low speeds and low Reynolds numbers.

What can we do without flapping the wings?

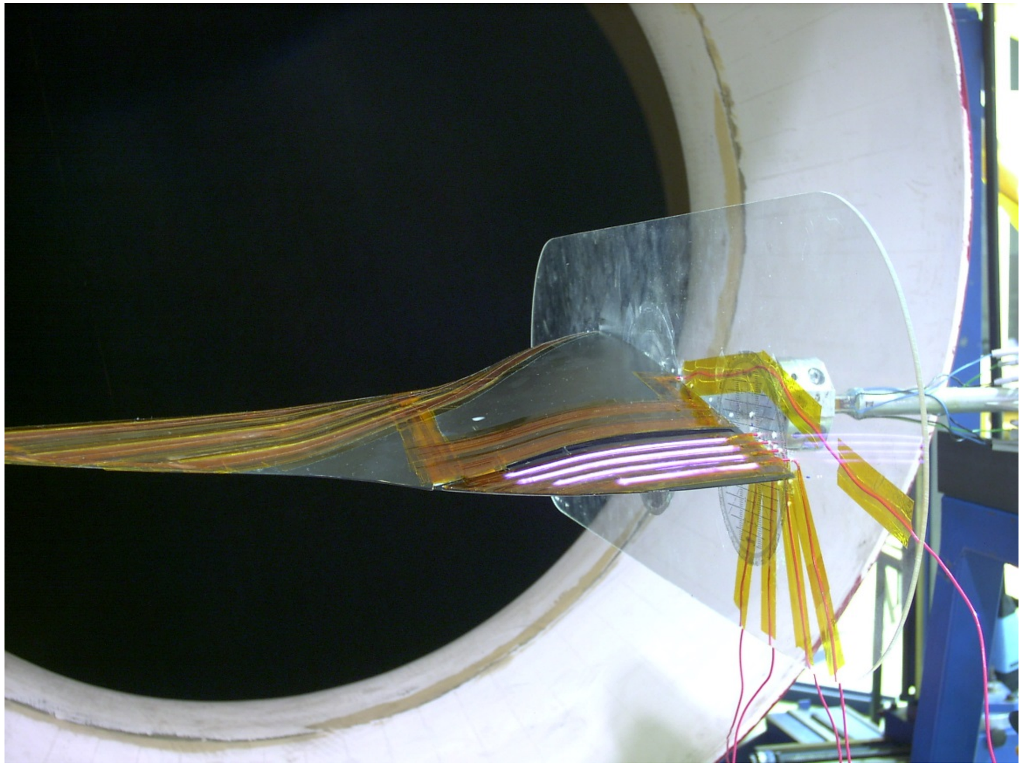


Stall speed as a function of maximum lift coefficient

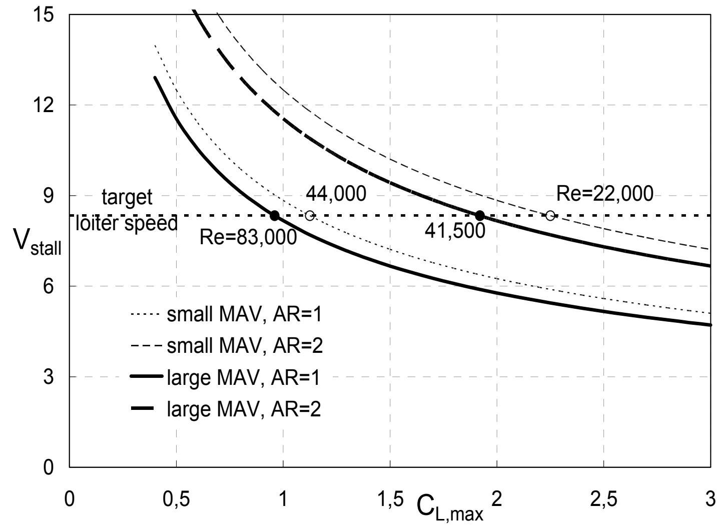
Motivation

Motivation for Mini (<1.6m) and Micro UAVs (<0.8m)

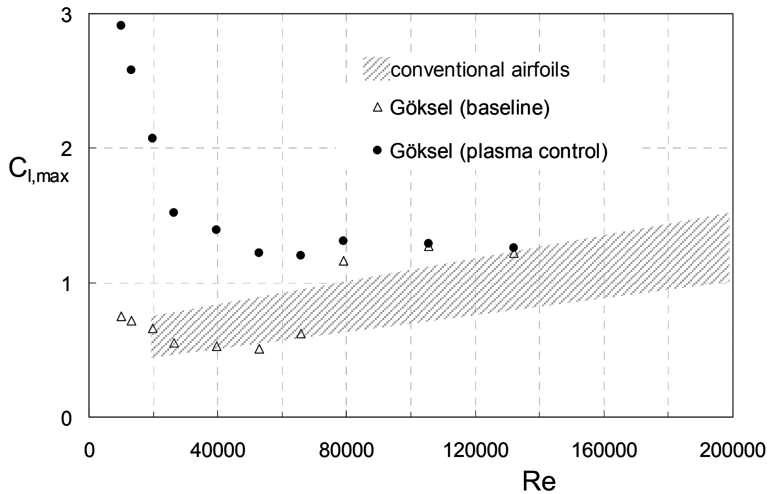
Flapping the fields! Pulsed plasma actuators could serve as plasma slats and plasma flaps for active separation and circulation control.



Let‘s Apply Plasma Flow and Plasma Roll Control on B-ionic Flying Wing Models



Stall speed as a function of maximum lift coefficient



Plasma control data using corona discharges (~8.5 W)

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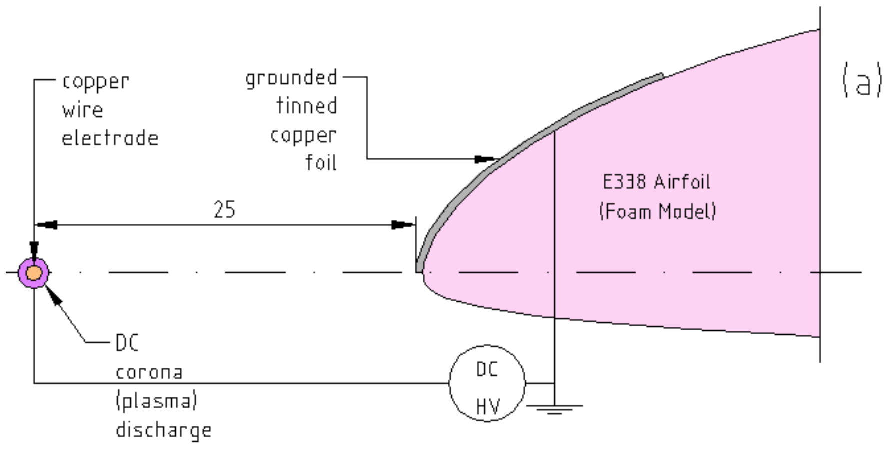
Flying Wing Airfoils

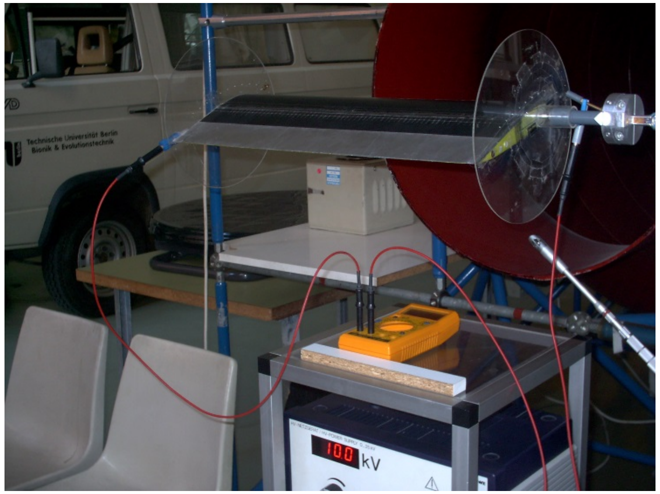
Eppler E338 Flying Wing Airfoils in Wind Tunnel

Tests Run at 20,000 ≤ Re ≤ 140,000 (Airfoil)

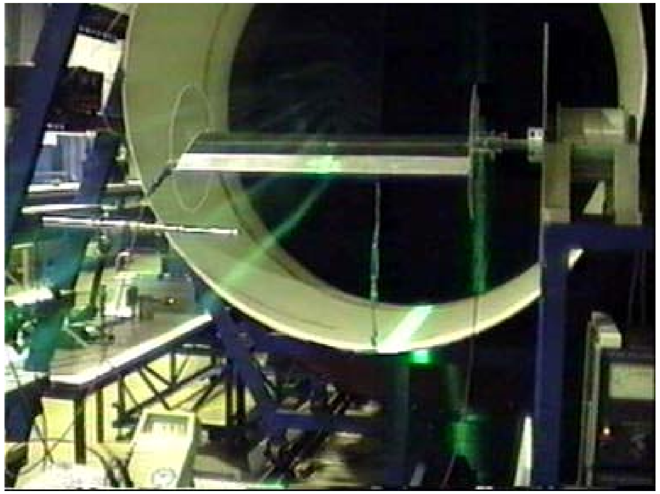
DC High Voltage (10 – 20 kV, 0.2 – 10 W)



(a) Corona Discharge Plasma Actuator.



b=0.50 m, c=0.18 m, AR=2.8



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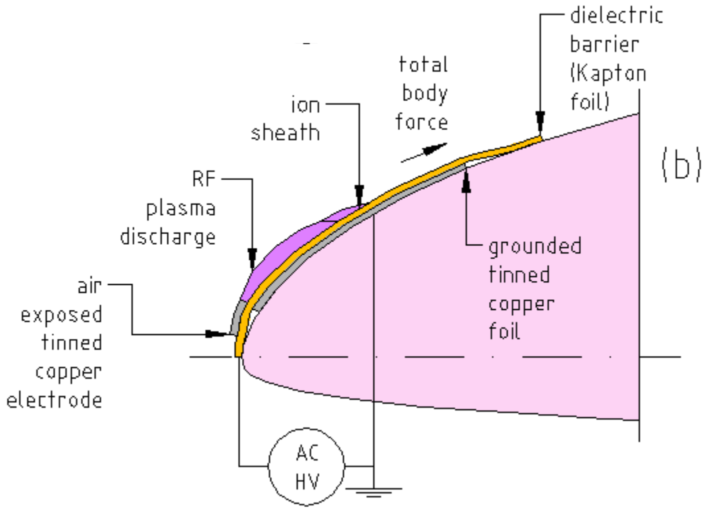
Flying Wing Airfoils

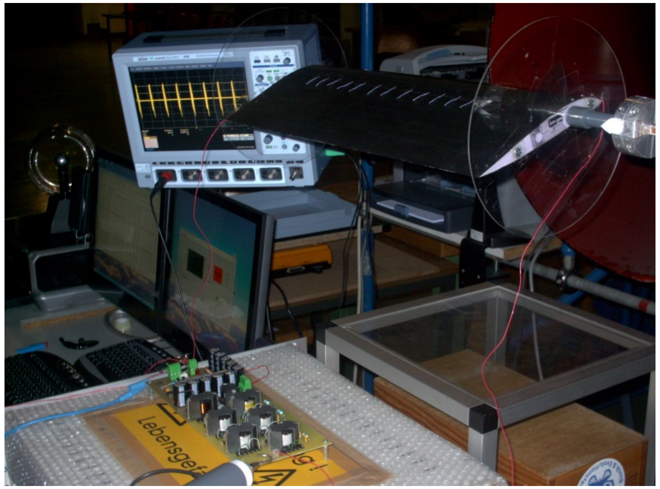
Eppler E338 Flying Wing Airfoils in Wind Tunnel

Tests Run at 20,000 ≤ Re ≤ 140,000 (Airfoil)

AC High Voltage (8 – 10 kVpp, 0.2 – 5.0 W)



(b) Dielectric Barrier Discharge Plasma Actuator.



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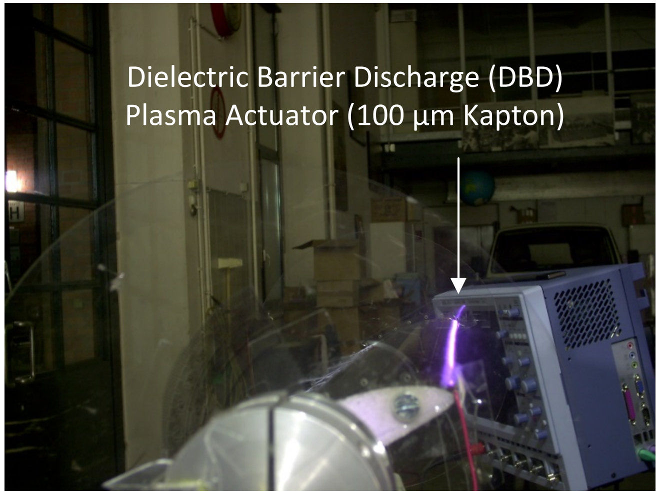

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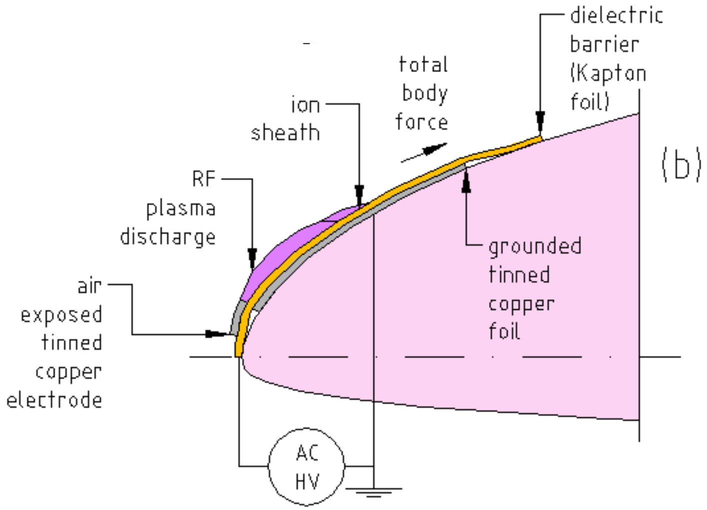
Flying Wing Airfoils

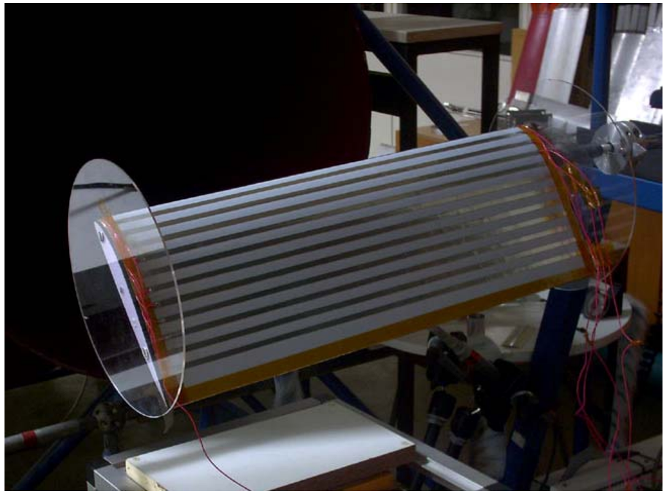
Eppler E338 Flying Wing Airfoils in Wind Tunnel

Tests Run at 20,000 $\leq$ Re $\leq$ 500,000 (Airfoil)

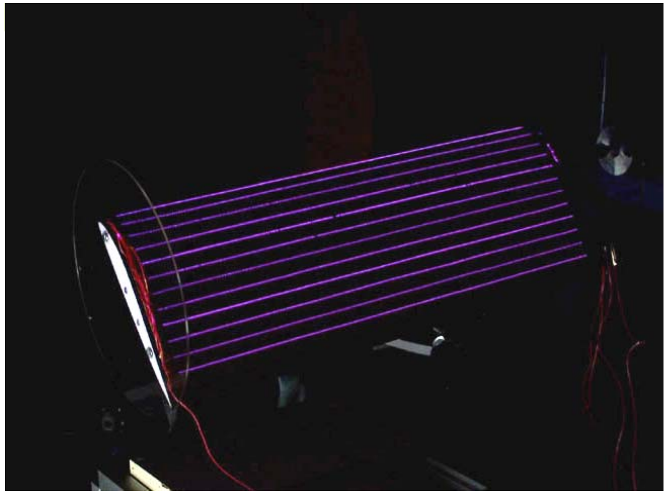
AC High Voltage (5 – 15 kVpp, 5.0 – 260 W)



(b) Dielectric Barrier Discharge (DBD) Plasma Actuator.



Multi DBD plasma actuators as phased array



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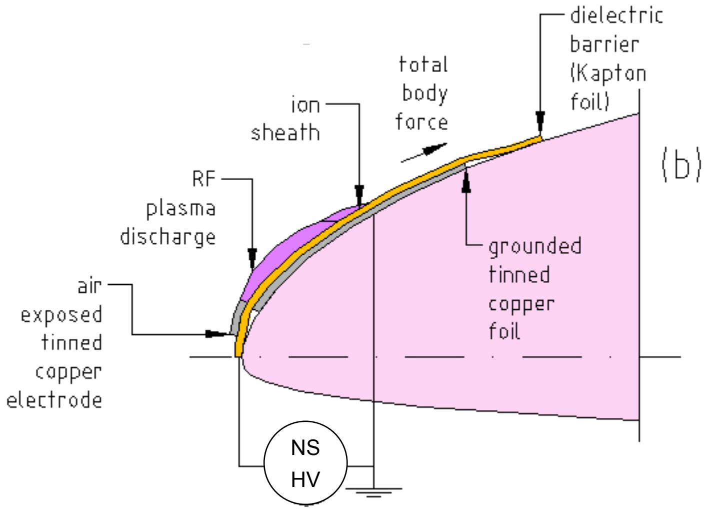
Flying Wing Airfoils

Eppler E338 Flying Wing Airfoils in Wind Tunnel

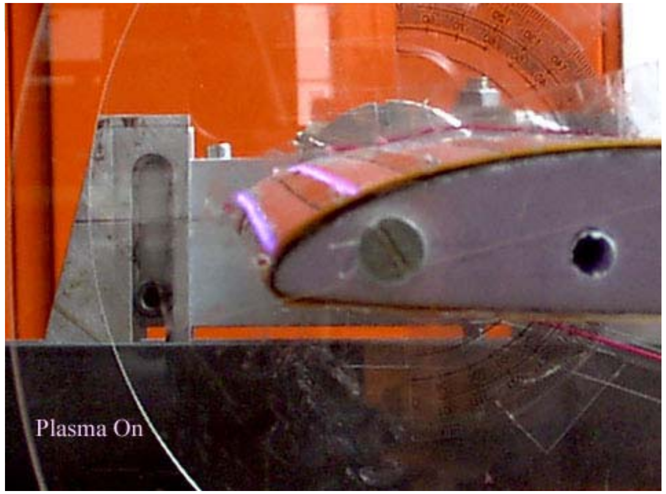
Tests Run at 20,000 $\leq$ Re $\leq$ 500,000 (Tube and 3D-Wing)

Nanosecond Pulsed High Voltage (5 – 25 kVp, 10 – 100 W)



(c) Nanosecond (NS) Pulse Driven DBD Plasma Actuator.

NS pulse driven ferroelectric cathode setup



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ELECTROFLUID SYSTEMS

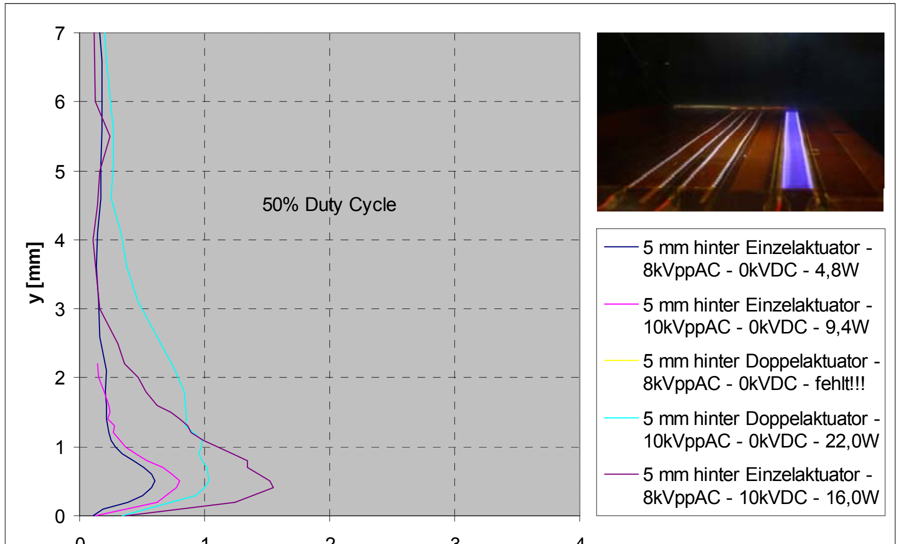
Flying Wing Airfoils

rtm Resources Technologies Management

Eppler E338 Flying Wing Airfoils in Wind Tunnel

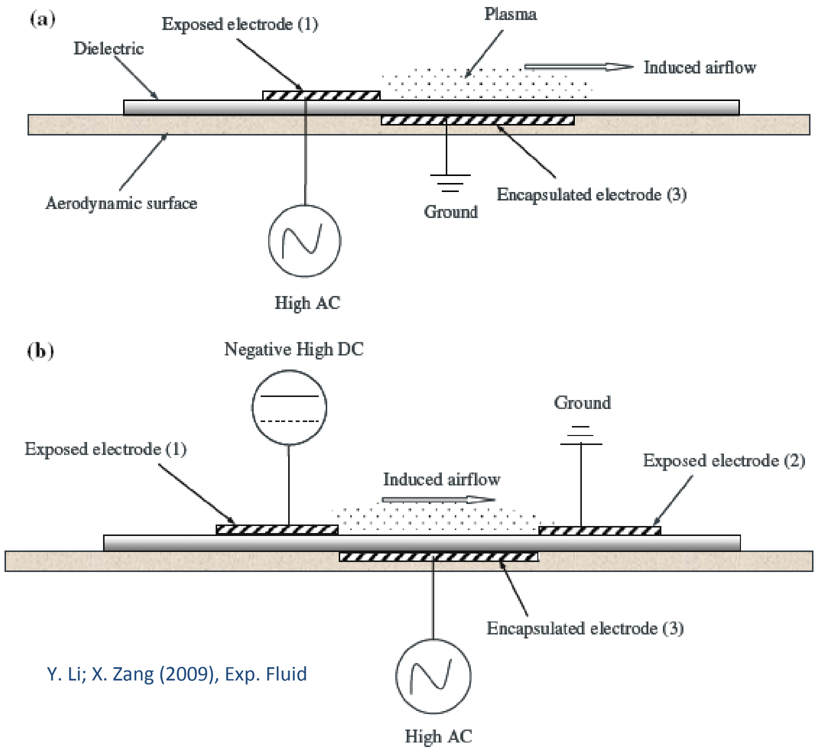
Tests Run at 50,000 ≤ Re ≤ 1,000,000 (3D-Wing)

AC/NS High Voltage (5 – 30 kVpp, 5.0 – 100 W) & DC High Voltage (10 – 20 kVp, 10 – 60 W)



B. Göksel (2013)

(d) Sliding Discharge Plasma Actuator.



Y. Li; X. Zang (2009), Exp. Fluid

Flying Wing Airfoils

Eppler E338 Flying Wing Airfoils in Wind Tunnel

Tests Run at 50,000 ≤ Re ≤ 1,000,000 (3D-Wing)

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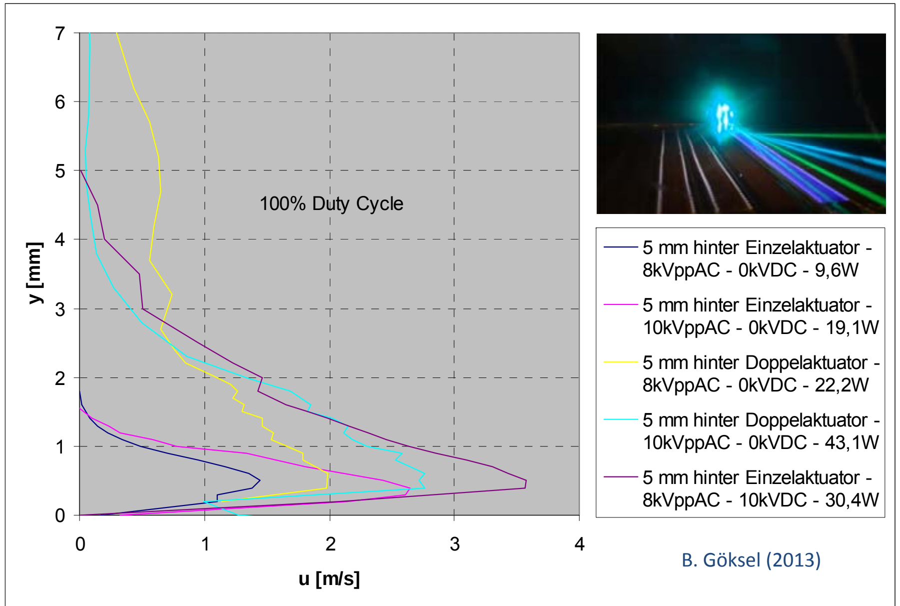

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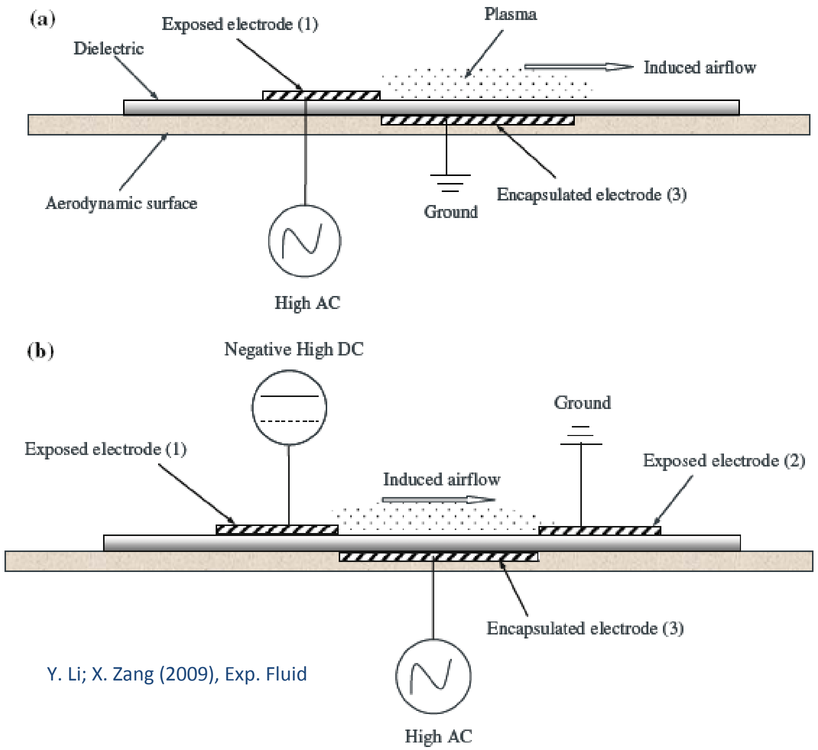

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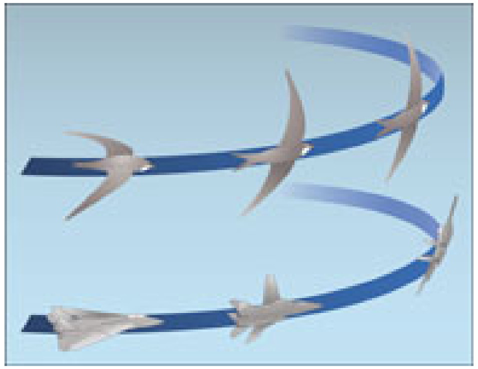
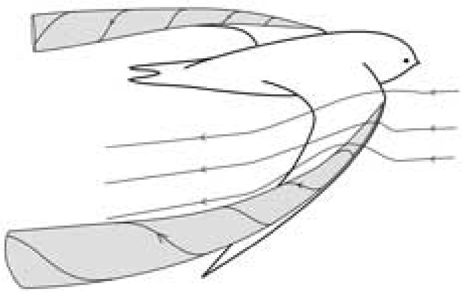
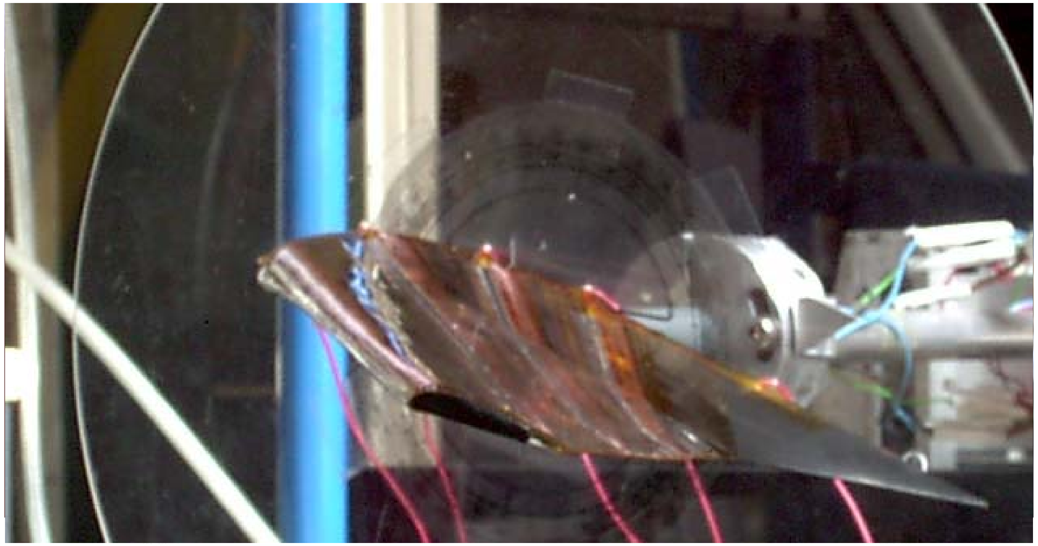
Flying Wing Half Models

Eppler E338 Flying Wing Half Models in Wind Tunnel with 60 cm and 120 cm Diameter



Videler, J. J.; Stamhuis, E. J.; Povel, G. D. E. (2004) Leading-Edge Vortex Lifts Swifts. *Science* **306** (Dec 10), pp. 1960-1962.





Reynolds number distribution for MAV flying wing half-span (38 cm) wing model at typical cruise speed of 11.1 m/s (40 km/h, 25 mph).

b=0.39 m, c=0.48 m, AR=2.0

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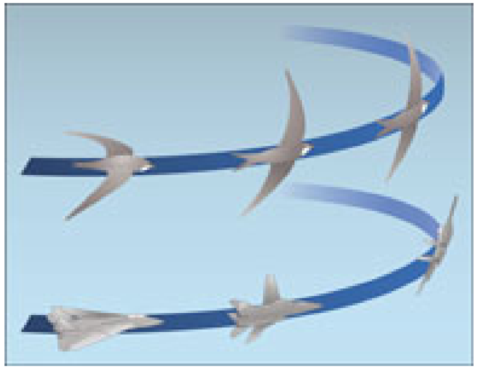
Flying Wing Half Models

Eppler E338 Flying Wing Half Models in Wind Tunnel with 60 cm and 120 cm Diameter



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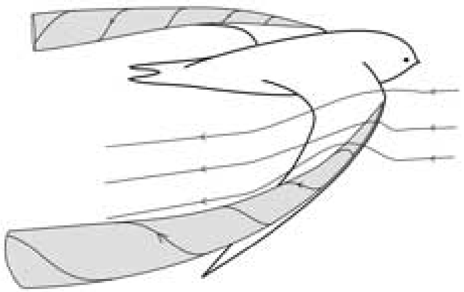

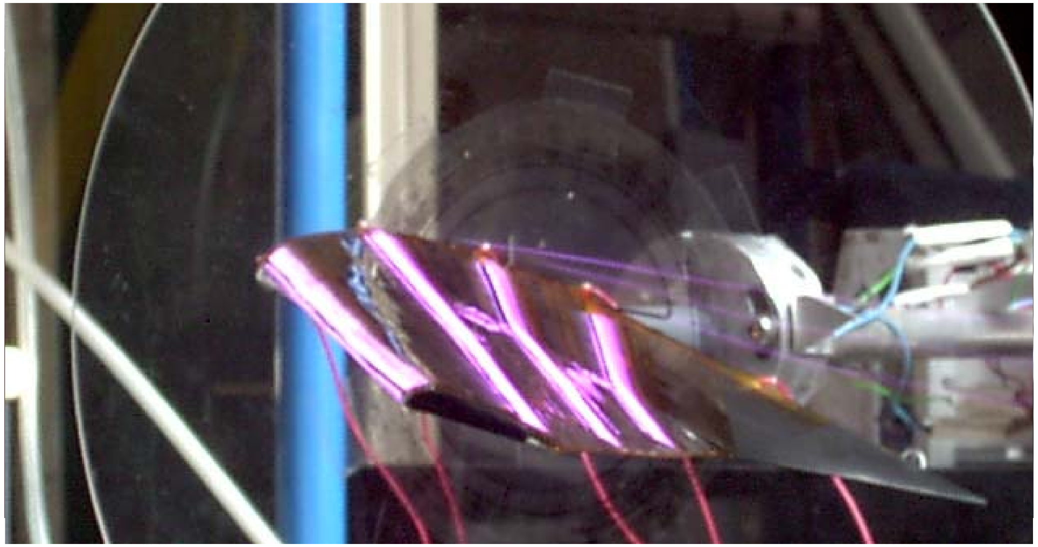

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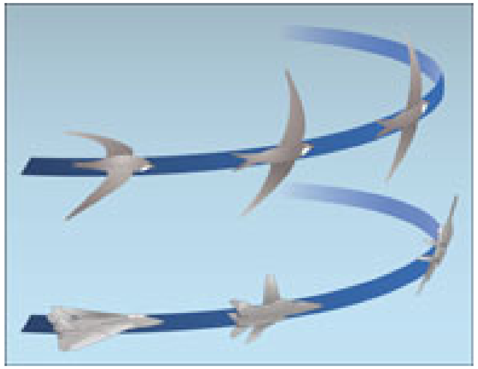

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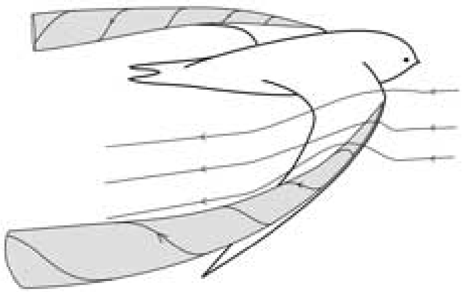

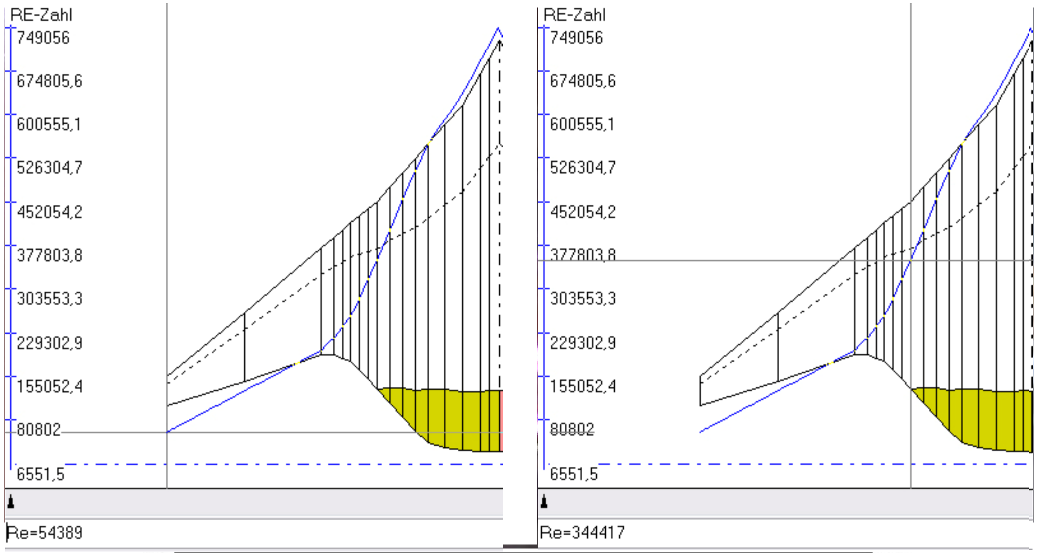

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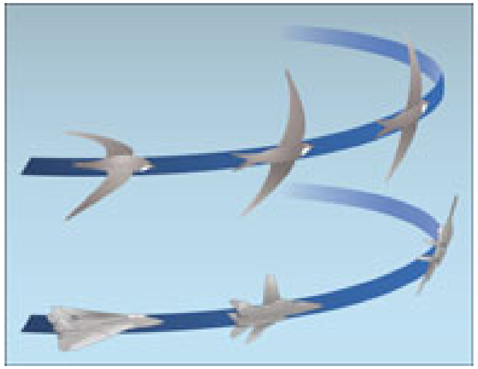
Eppler E338 Flying Wing Half Models in Wind Tunnel with 60 cm and 120 cm Diameter



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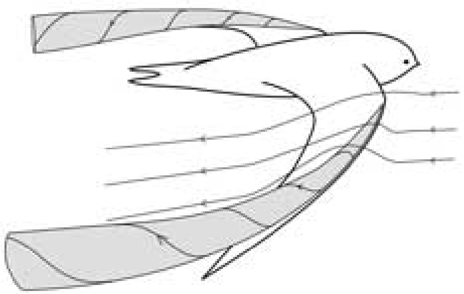

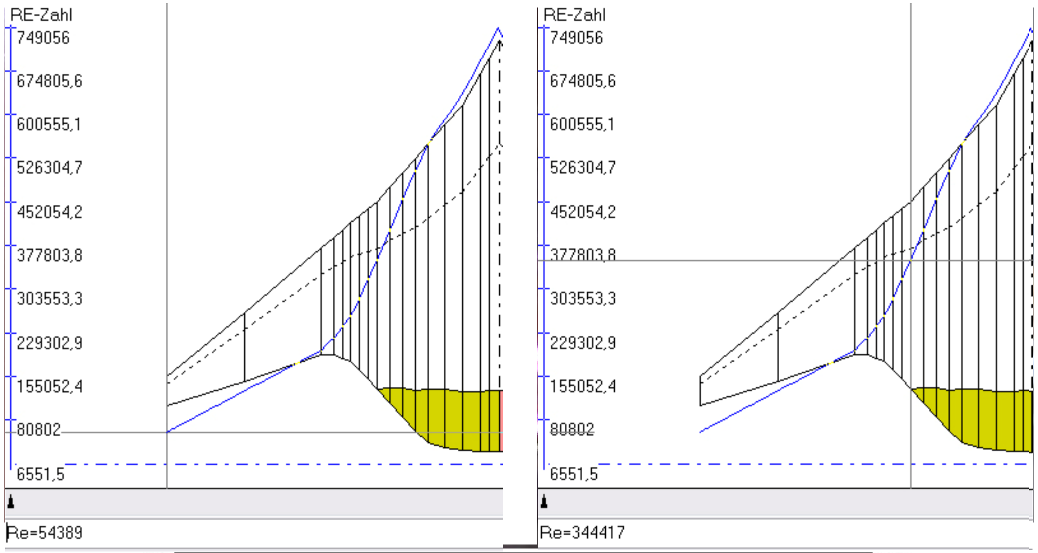

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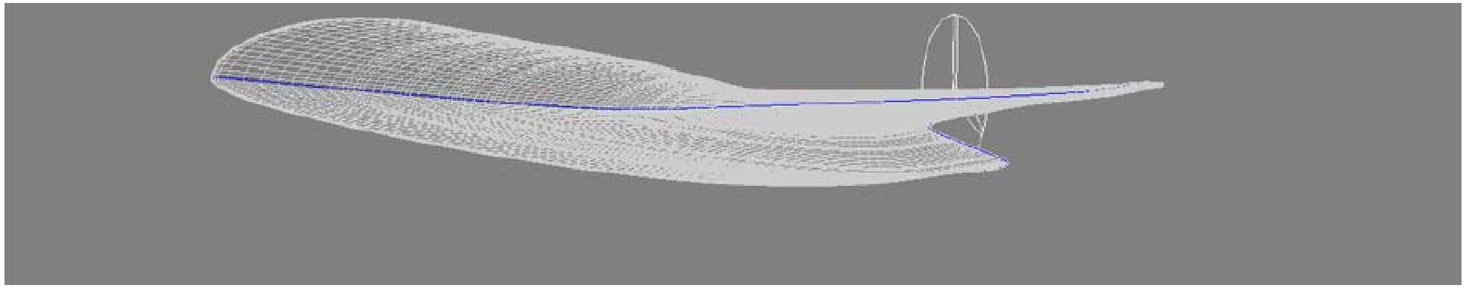
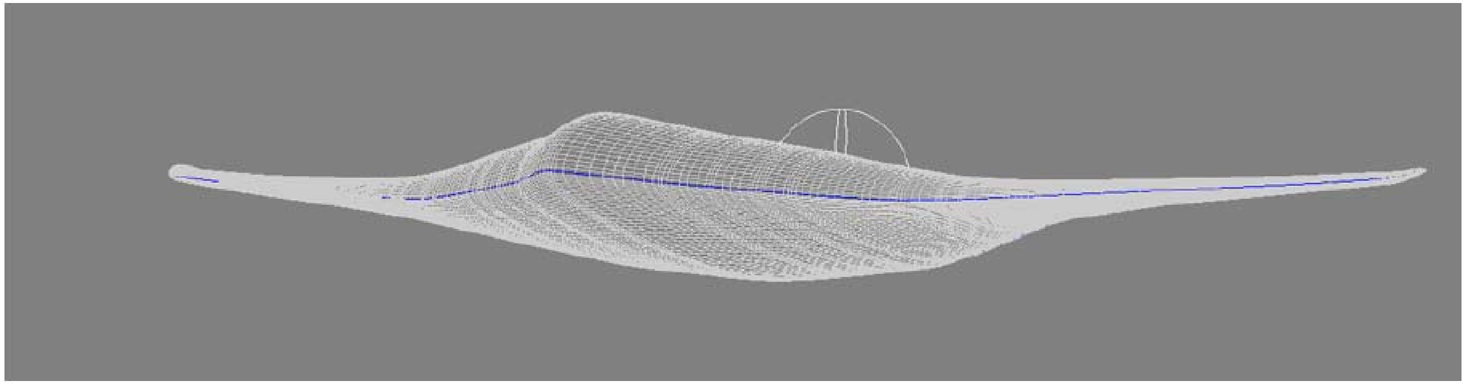
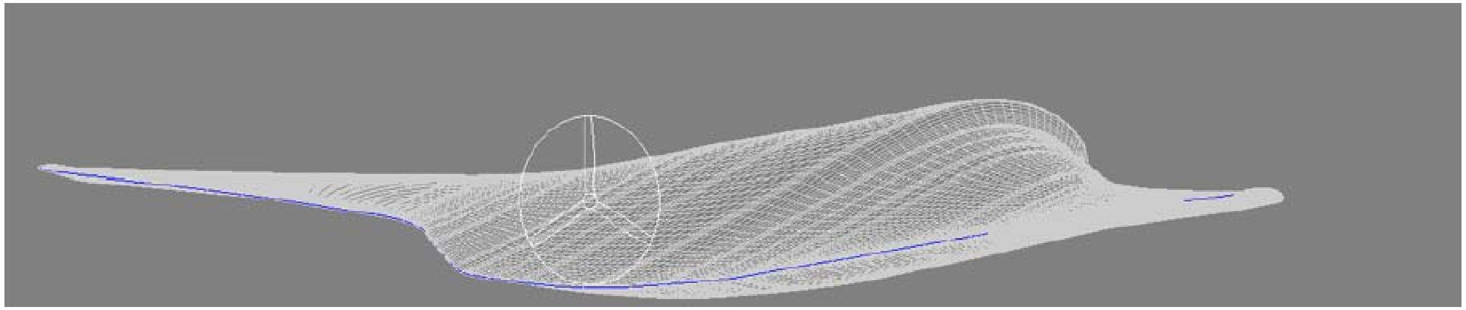
Flying Wing Flight Models

Multi DBD Plasma Mini UAV with 180 cm Span Width and 4.99 kg Weight







Flying Wing Flight Models

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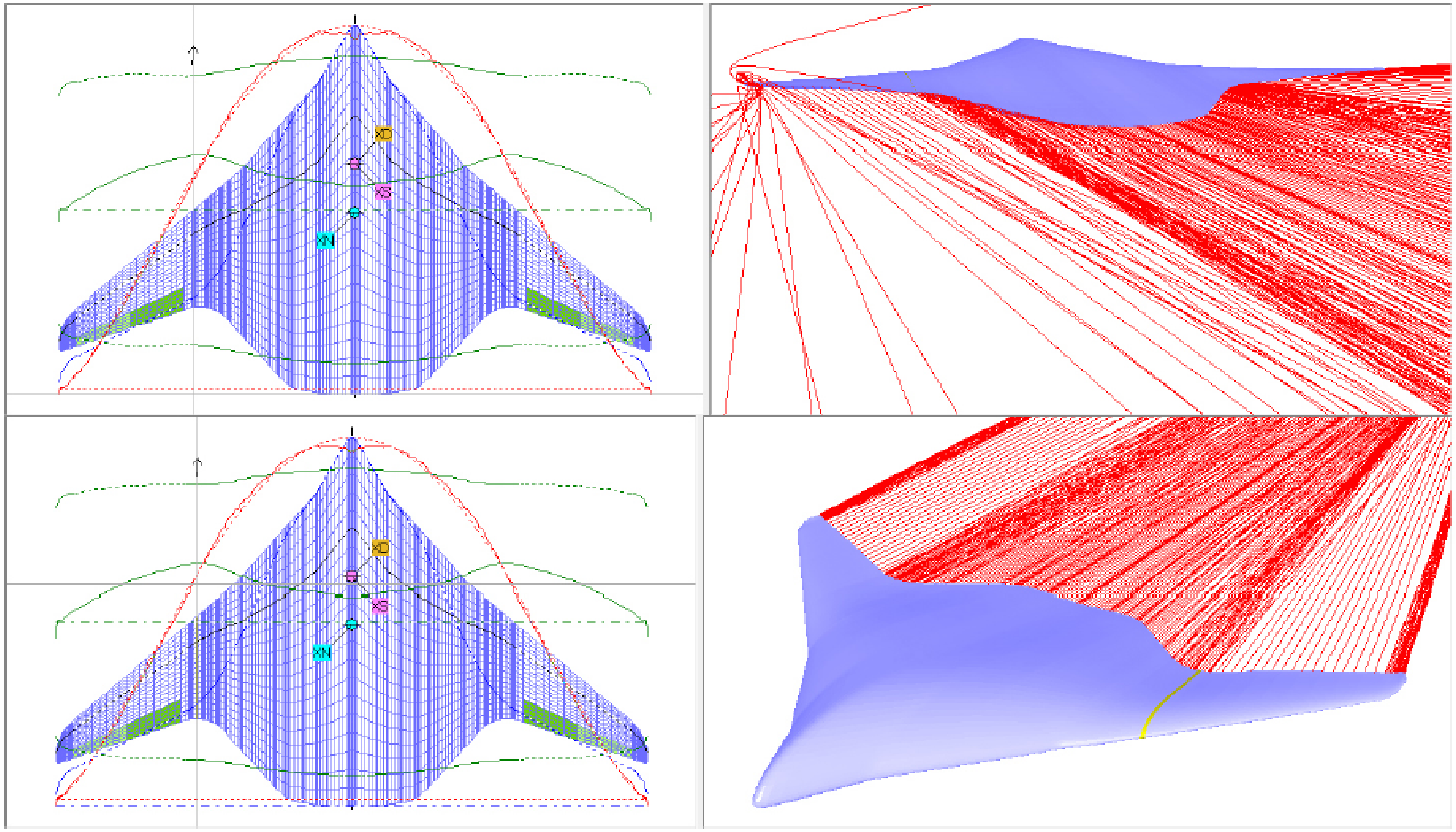

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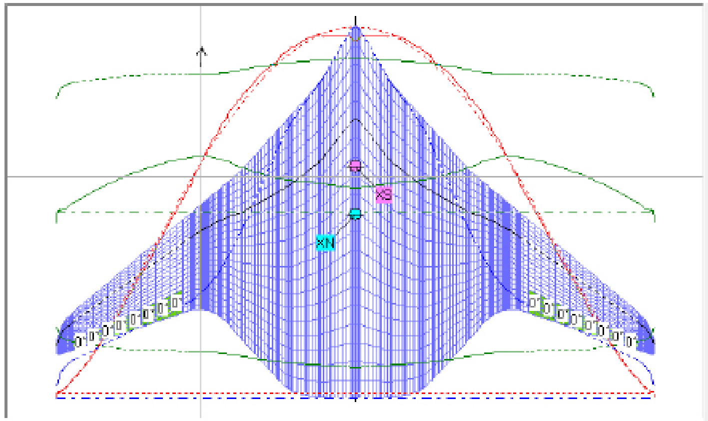

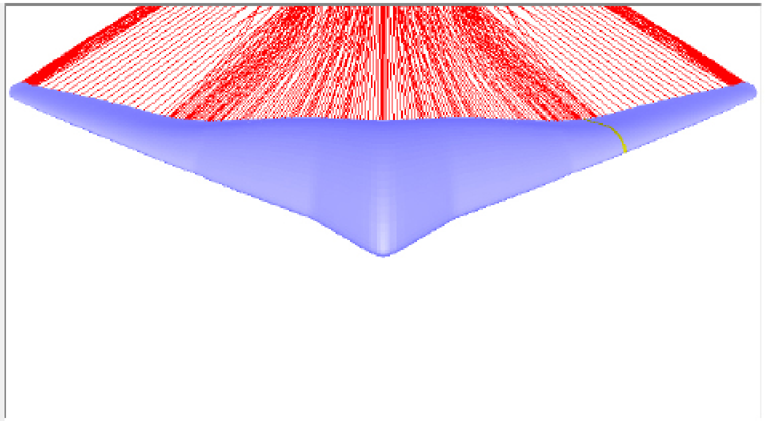

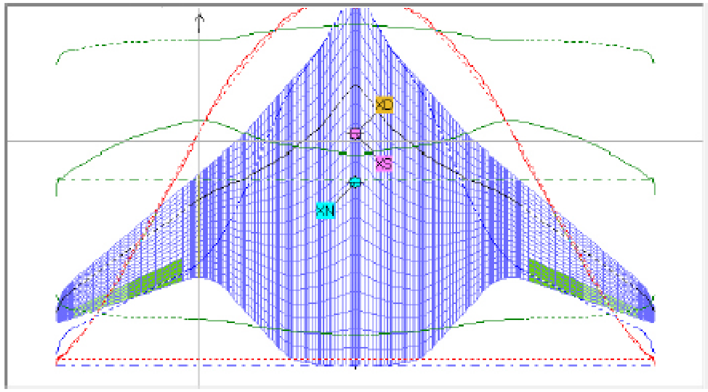

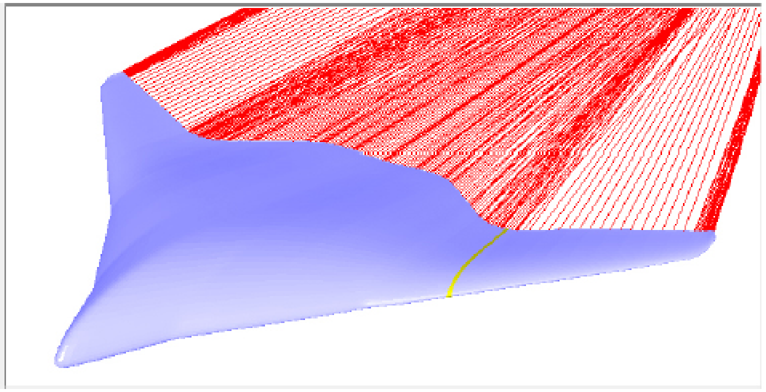

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Airfoil Performance

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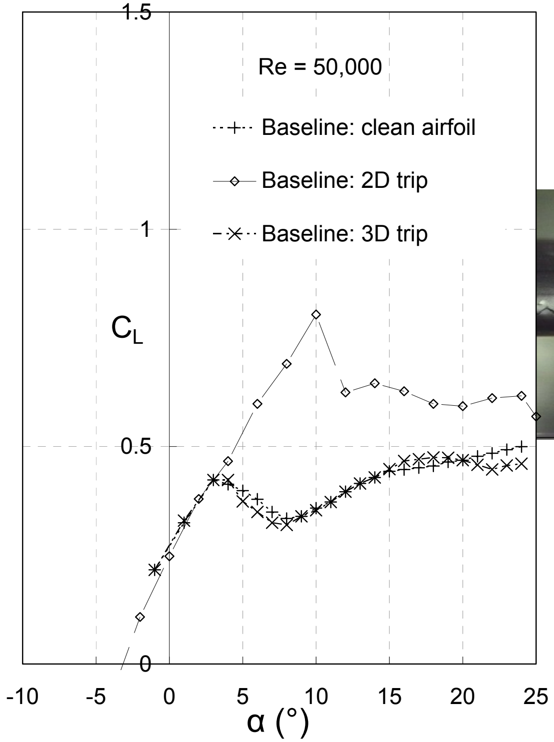
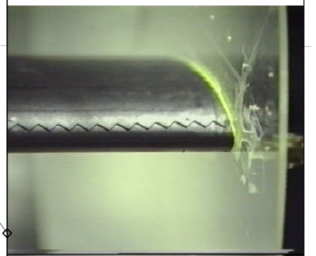
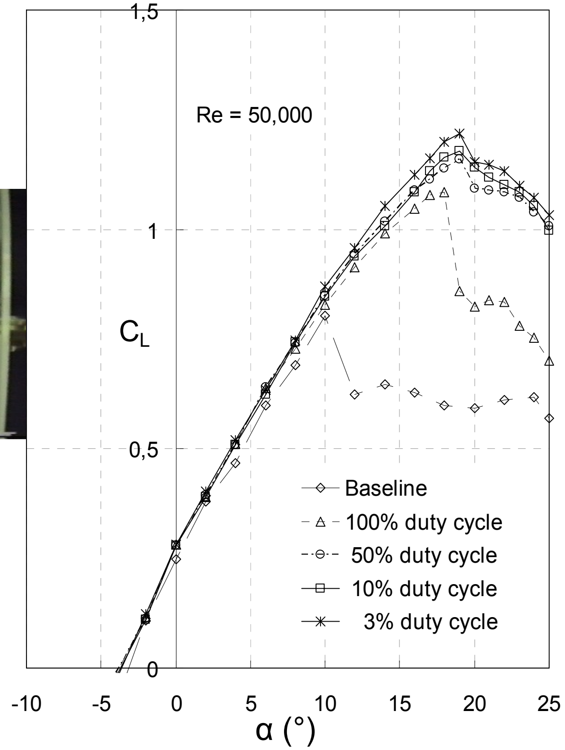
Dielectric Barrier Discharge Plasma: 8 – 10 kVpp, 0.2 – 5.0 W

Boundary Layer Tripping





Boundary Layer Control with Plasma Actuator



Example of the effect of boundary layer tripping and plasma actuation at $F^{+}=1$ on airfoil performance at Reynolds number Re=50,000.

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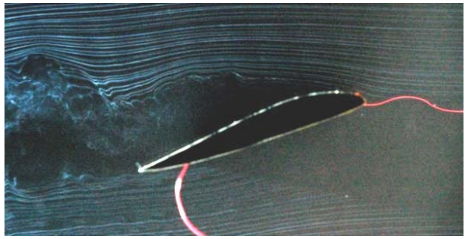
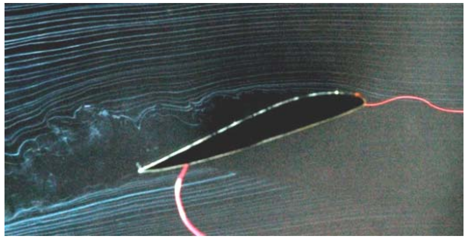
Airfoil Performance

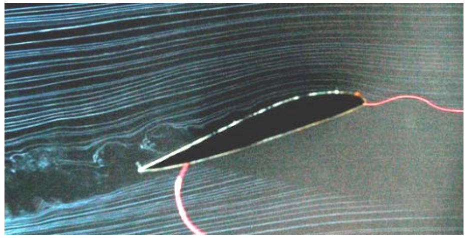
Dielectric Barrier Discharge Plasma: 8 – 10 kVpp, 0.2 – 5.0 W



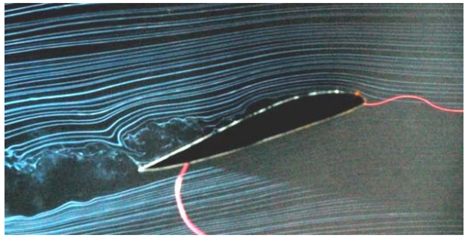
(a) 0% duty cycle (0kVpp)



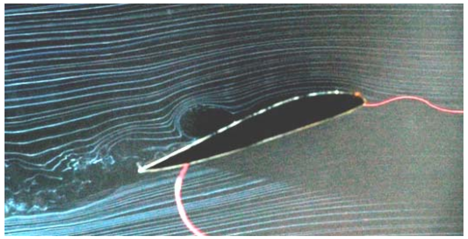
(b) 100% duty cycle



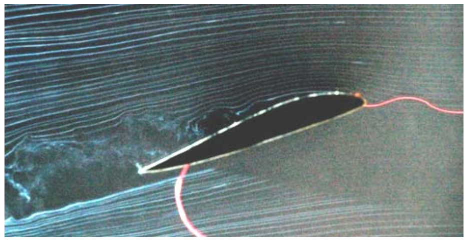
(c) 50% duty cycle (F+=1)



(d) 10% duty cycle (F+=1)

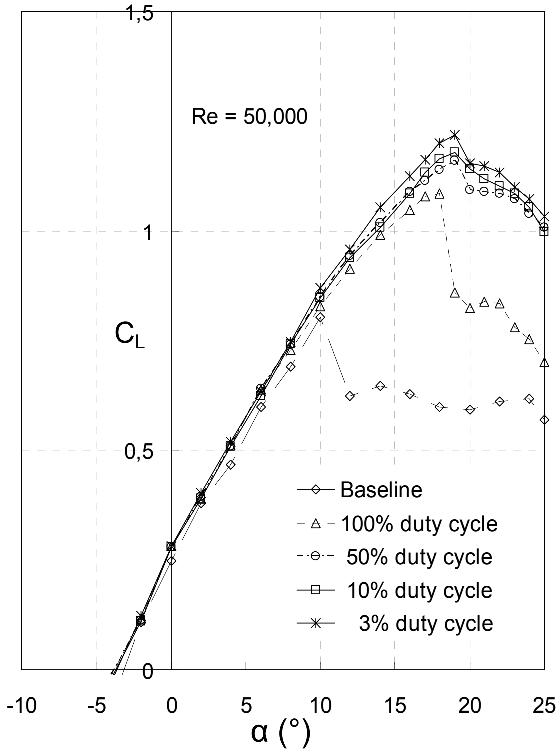


(e) 3% duty cycle (F+=1)



(f) 1% duty cycle (F+=1)

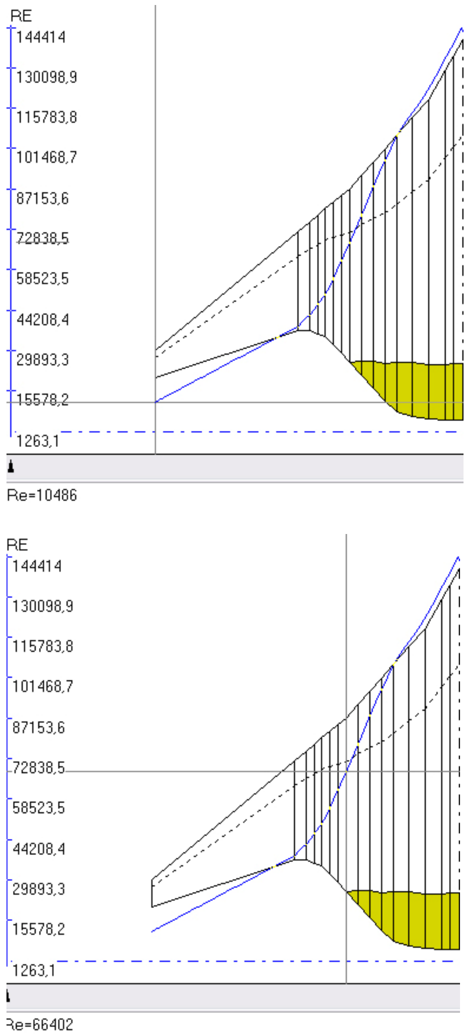
Boundary Layer Control with Plasma Actuator

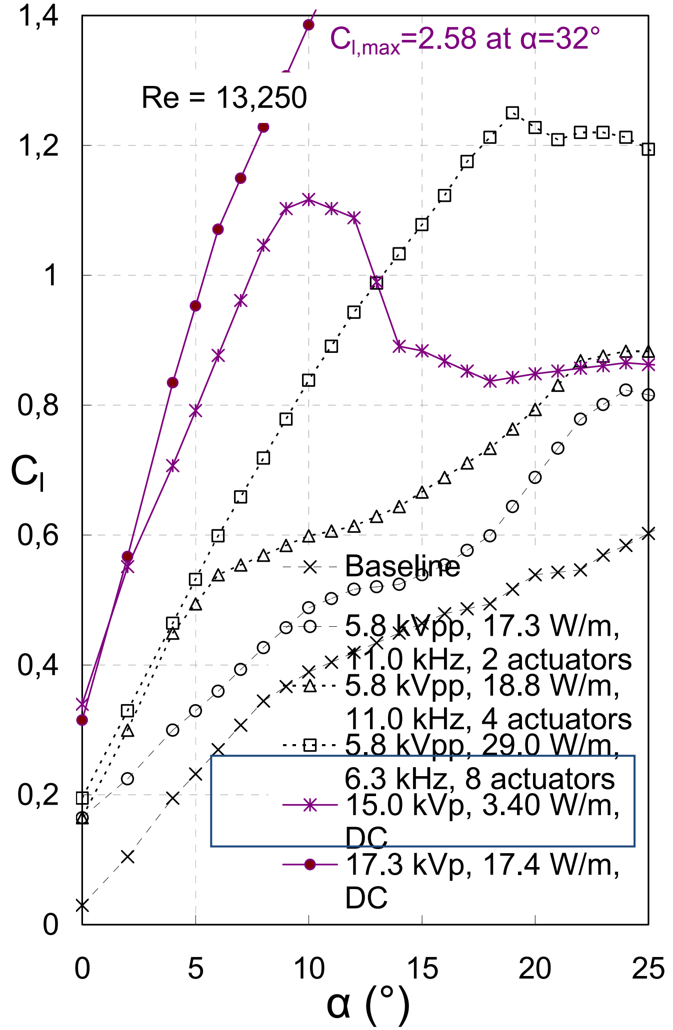


Airfoil Performance

Multi Dielectric Barrier Discharge Plasma: 4 – 6 kVpp, 5 – 30 W

30 cm MAV





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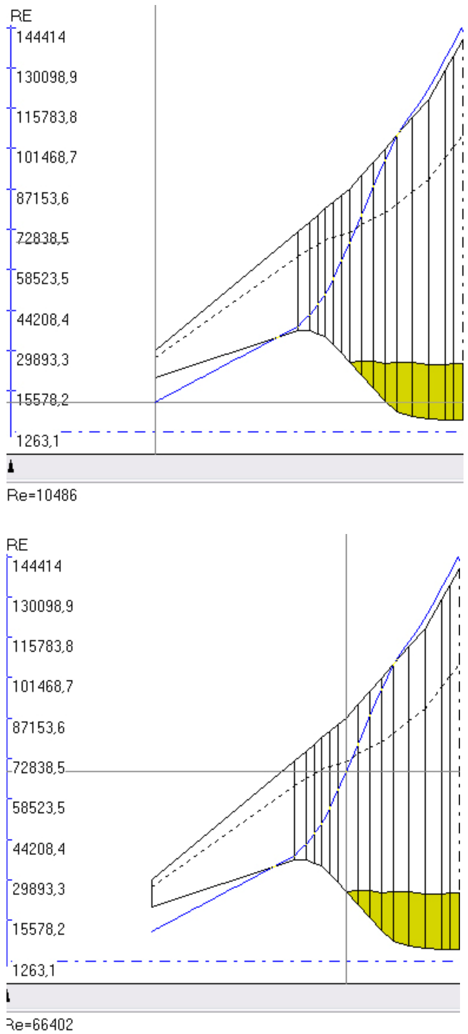
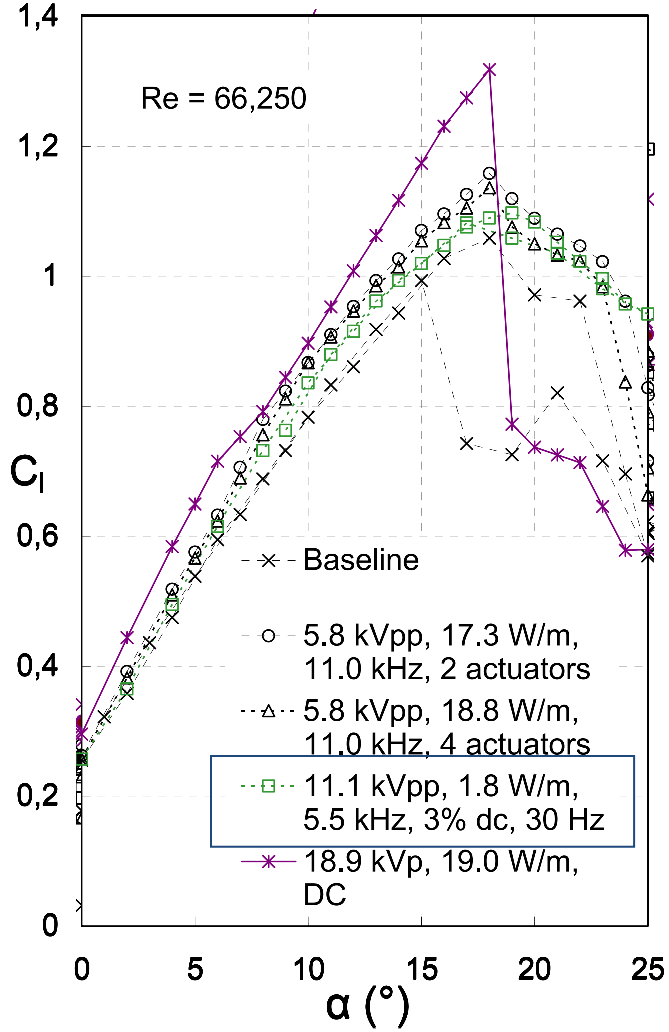
Airfoil Performance

Multi Dielectric Barrier Discharge Plasma: 4 – 6 kVpp, 5 – 30 W

30 cm MAV





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  - Optimization Study
  - Half Wing Performance
- Conclusions and Outlook

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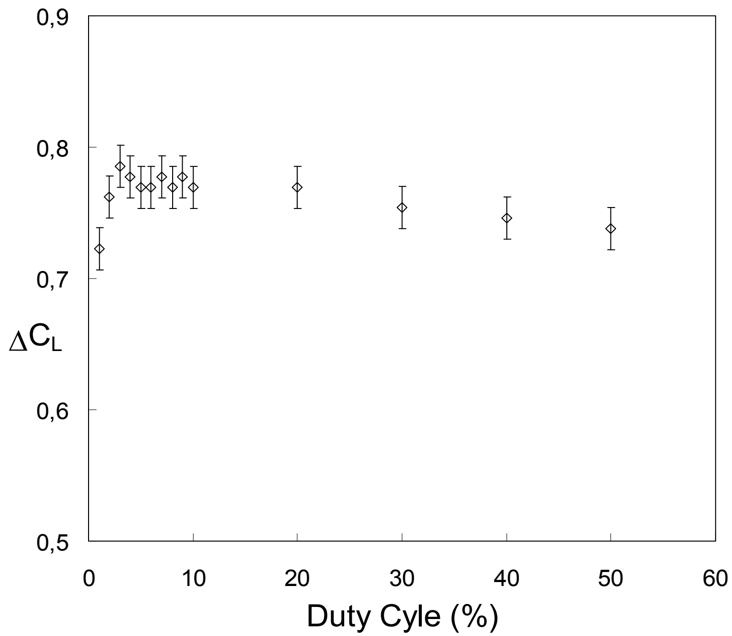
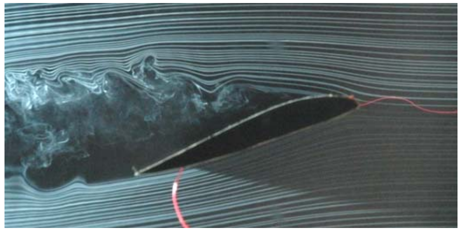
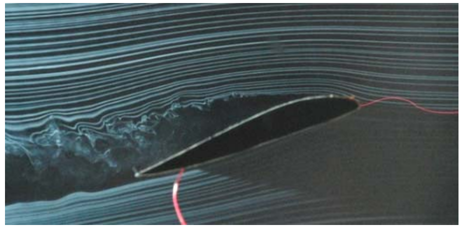
Optimization Study

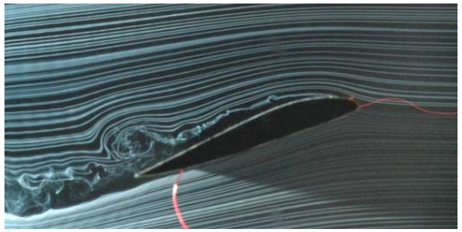
Smoke Wire Flow Visualization at Re=20,500 (F+=1 → f=9.6 Hz)

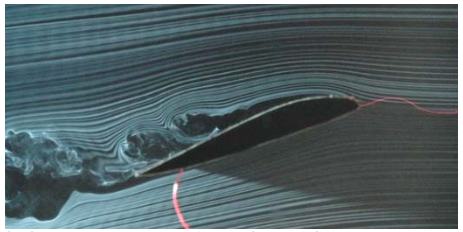


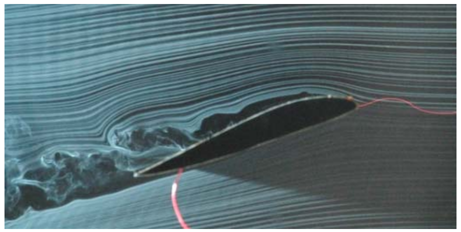
Effect of duty cycle on post-stall (α=18° airfoil lift at a low MAV Reynolds number; Re=20,500).

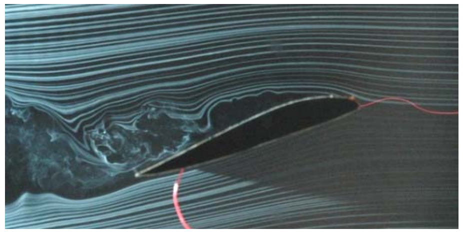

(a) 0% duty cycle (0kVpp)


(b) 100% duty cycle


(c) 90% duty cycle (F^{+}=1)


(d) 50% duty cycle (F^{+}=1)


(e) 30% duty cycle (F^{+}=1)


(f) 10% duty cycle (F^{+}=1)

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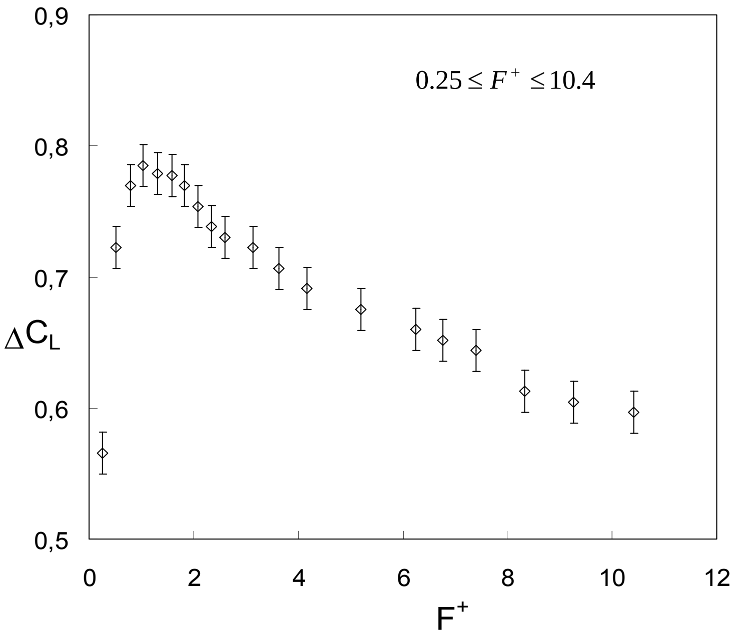
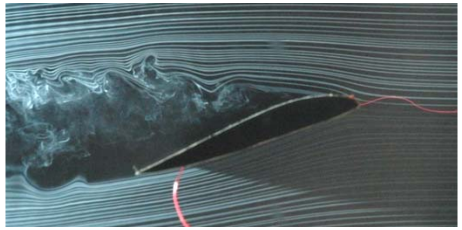
Optimization Study

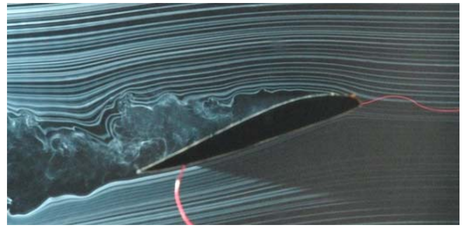
Smoke Wire Flow Visualization at Re=20,500 (F+=1 → f=9.6 Hz)



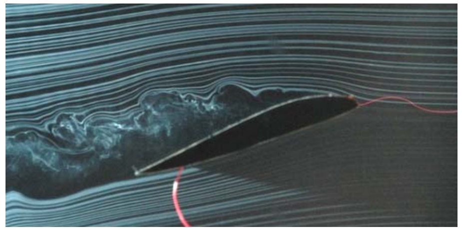
Effect of Strouhal number on post-stall (α=18° airfoil lift at a low MAV Reynolds number; Re=20,500). C_μ=0.05% and duty cycle = 3%.



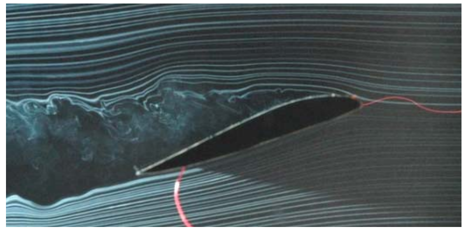
(a) 0% duty cycle (F^+=0)



(b) 3% duty cycle (F^+=1)



(c) 3% duty cycle (F+=2)

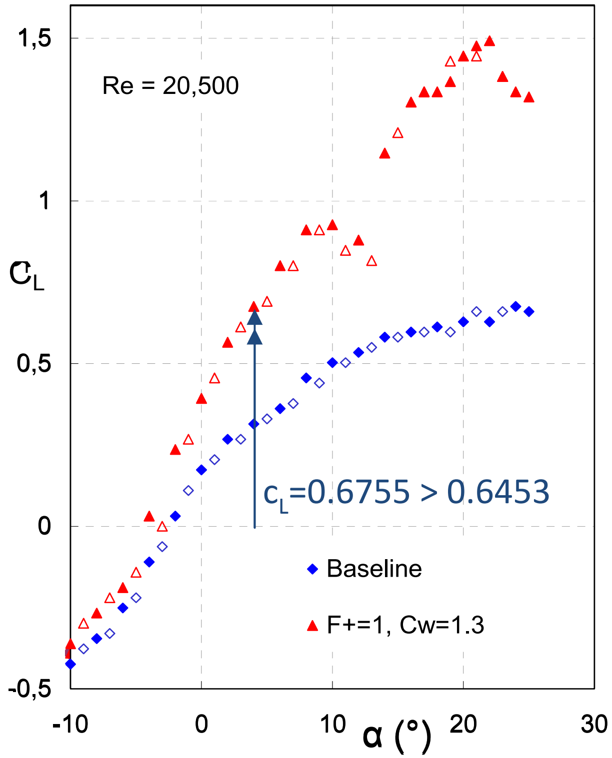


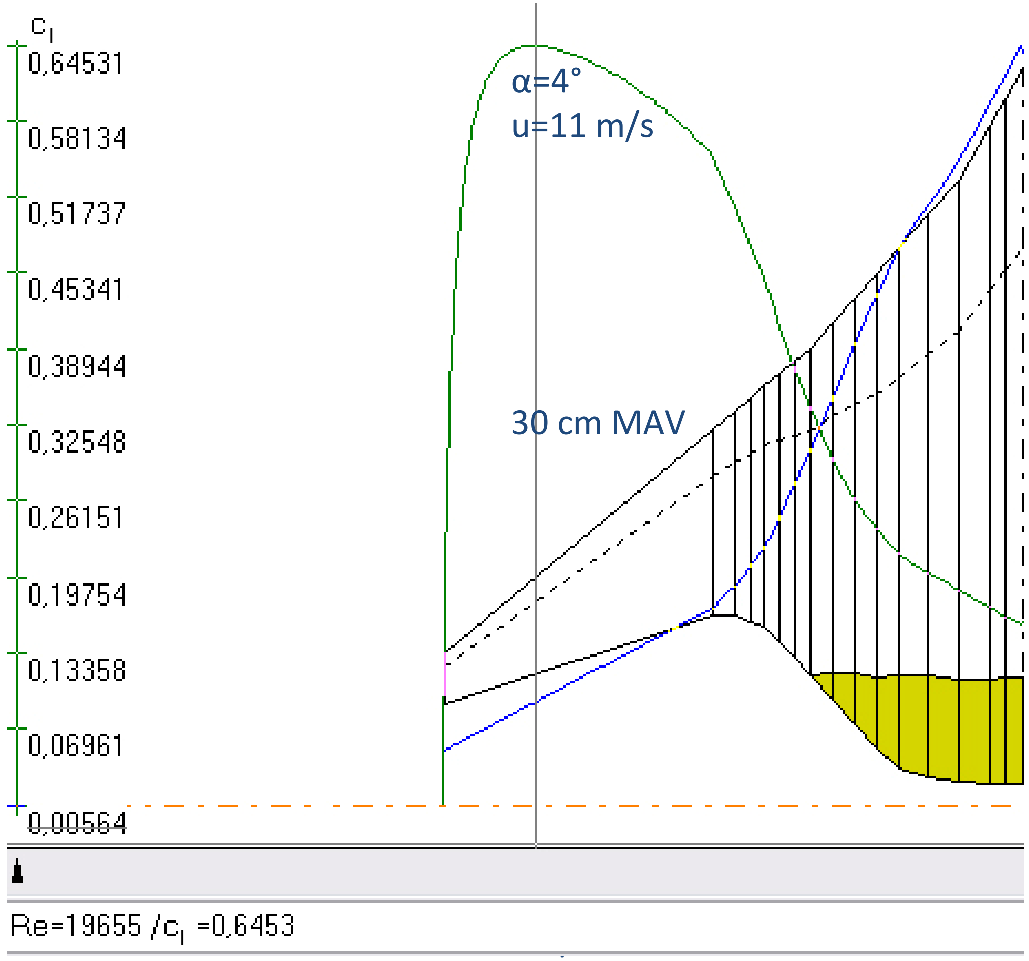
(d) 3% duty cycle (F+=3)

Examples of flow visualization photographs at different reduced frequencies for α=18° at Re=20,500 without and with the plasma actuator on. Larger lift is generally associated with larger downward deflection of the streamlines. Here it can be seen that the greatest deflections occur at F^+=1 and that the wakes associated with higher frequencies are larger.

Optimization Study

Smoke Wire Flow Visualization at Re=20,500 (F+=1 → f=9.6 Hz)





Effect of plasma actuation (8kVpp with 5mW/cm and 10kVpp with 9mW/cm or 0.9W/m at 4kHz), duty cycle = 3%.

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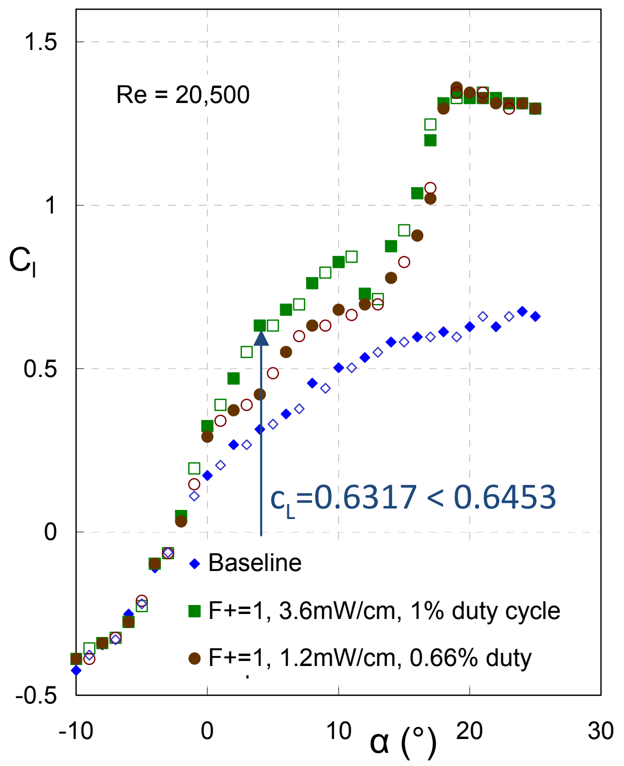
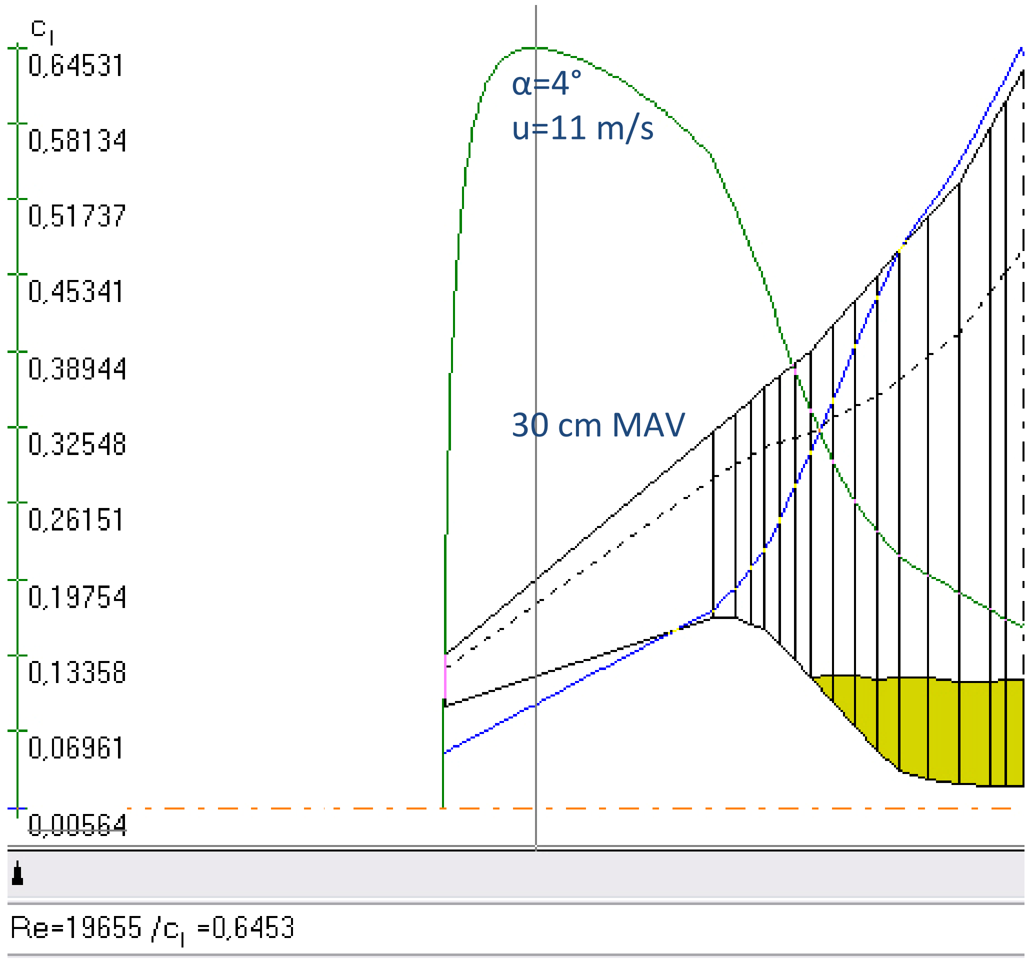
Optimization Study

Smoke Wire Flow Visualization at Re=20,500 (F+=1 → f=9.6 Hz)





Effect of plasma actuation (10kVpp with 3.6mW/cm and 9kVpp with 1.2mW/cm at 4kHz), duty cycle = 0.66%.

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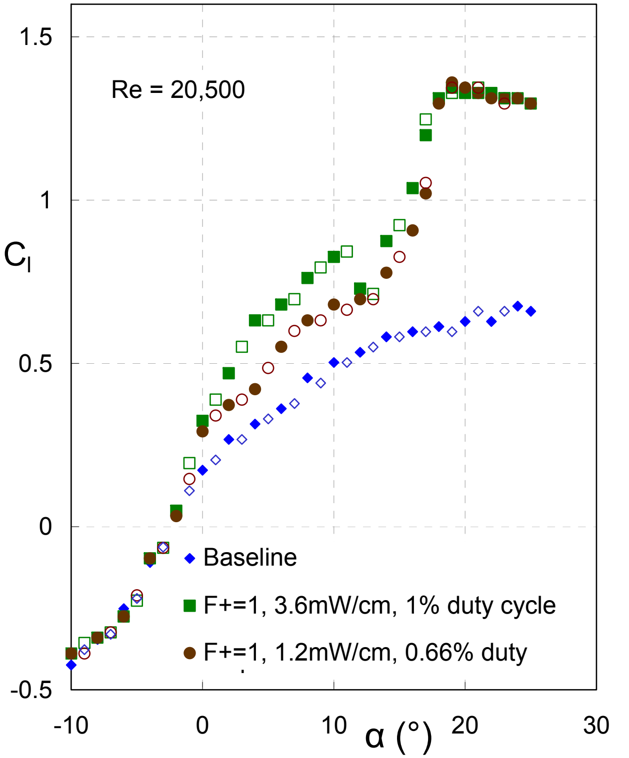
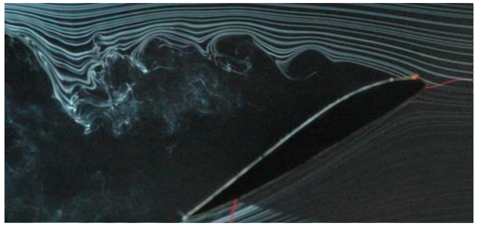
Optimization Study

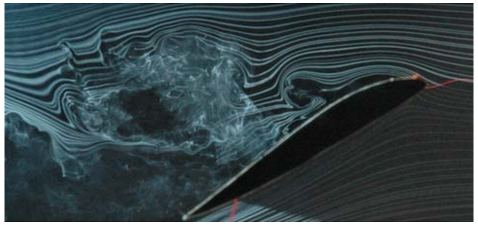
Smoke Wire Flow Visualization at Re=20,500 (F+=1 → f=9.6 Hz)



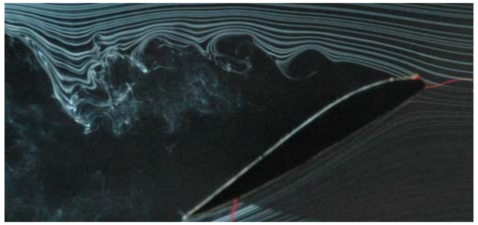
Effect of plasma actuation (10kVpp with 3.6mW/cm and 9kVpp with 1.2mW/cm at 4kHz), duty cycle = 0.66%.



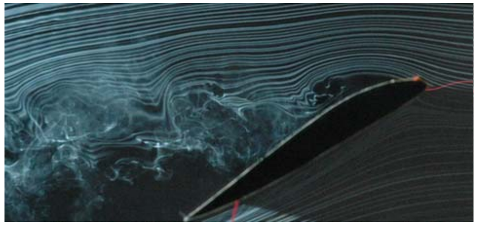
(a) 0% duty cycle (*F*+=0) (α=18°)



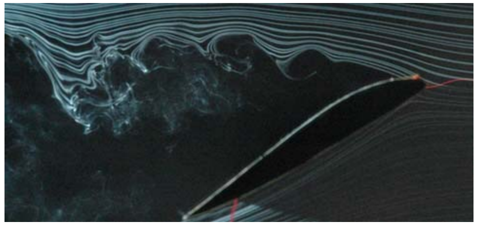
(b) 0.66% duty cycle (*F*+=1) (α=18°)



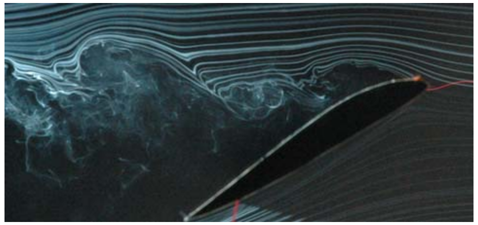
(c) 0% duty cycle (*F*+=0) (α=18°)



(d) 0.33% duty cycle (*F*+=1) (α=18°)



(e) 0% duty cycle (*F*+=0) (α=30°)



(f) 0.21% duty cycle (*F*+=1) (α=30°)

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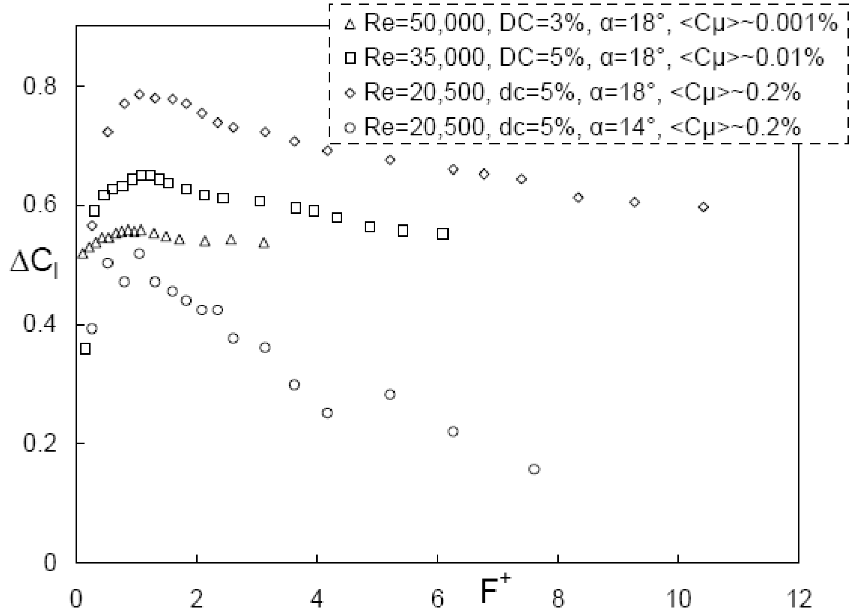
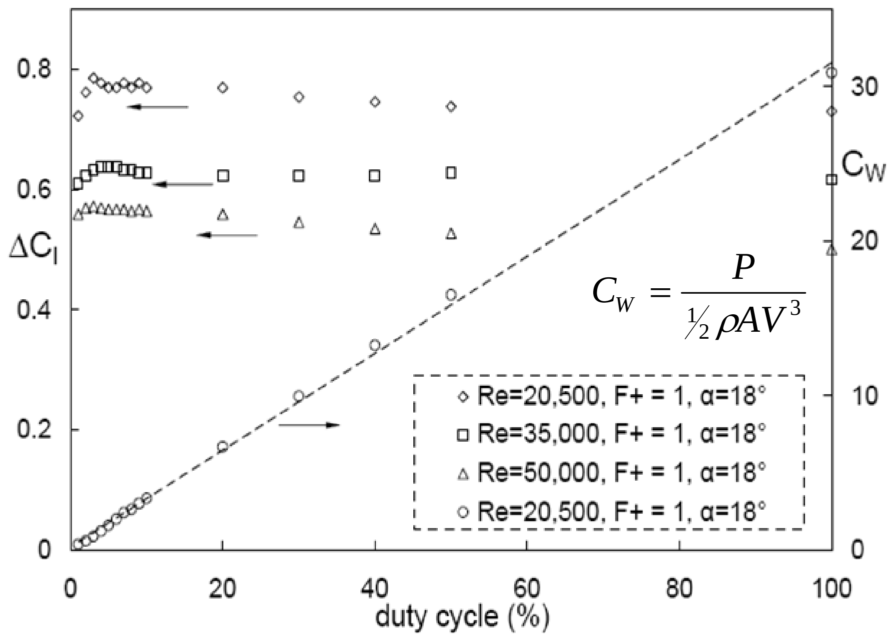
Optimization Study





Effect of reduced frequency on post-stall airfoil lift at different Reynolds numbers. Plasma at 10kVpp and 4kHz.

Effect of duty cycle on post-stall airfoil with plasma at 10kVpp and 4kHz for various Reynolds numbers. Corresponding measured power coefficient for Re=20,500.

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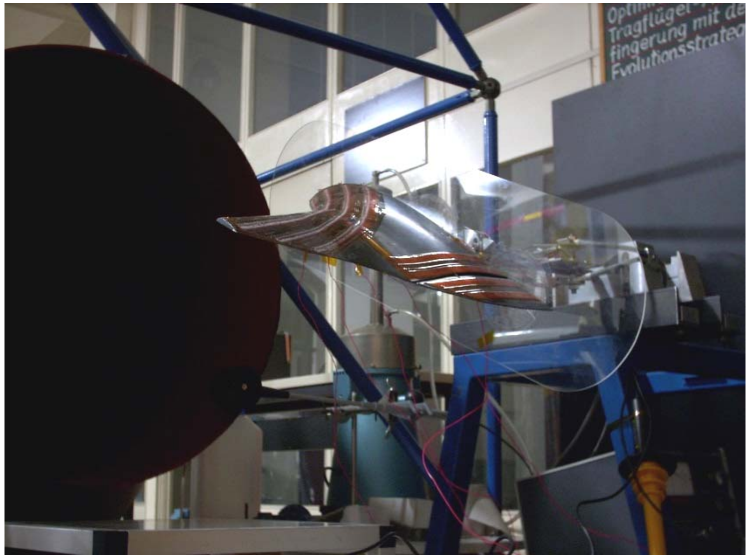
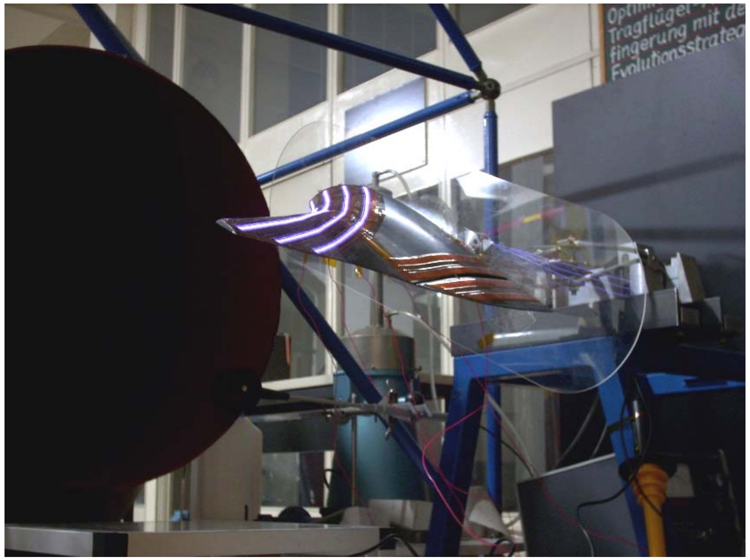
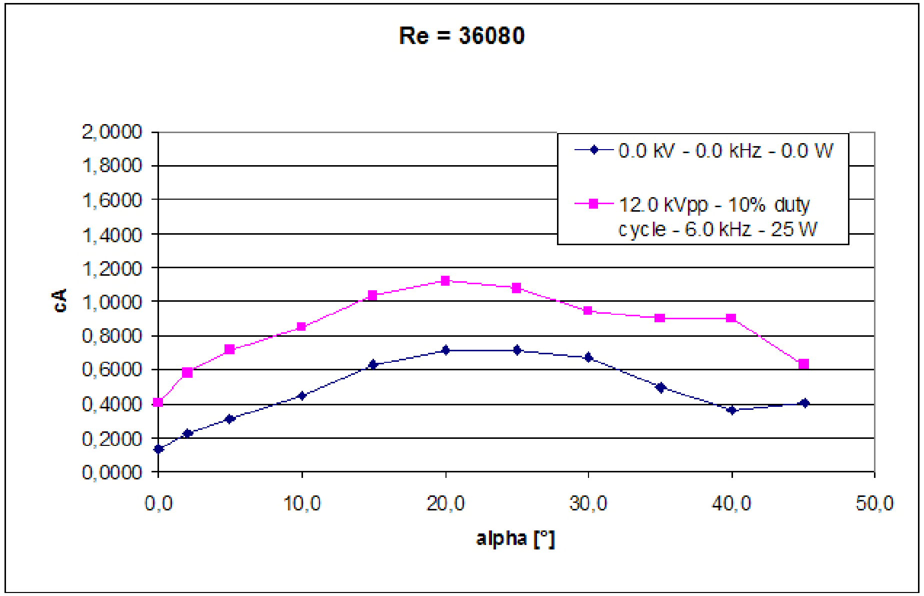
Half Wing Performance







Effect of phased plasma array with four leading edge actuators on half-span wing performance at a root Reynolds number (a) *Re*=36,080 (lift enhanced by max. 300%), (b) *Re*=216,000 (here by max. 60%) and (c) *Re*=393,000 (here by max. 25%)

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Half Wing Performance

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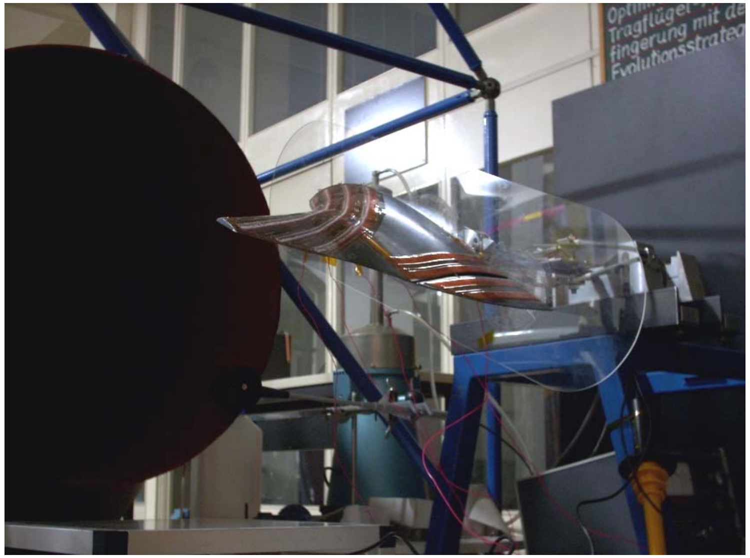
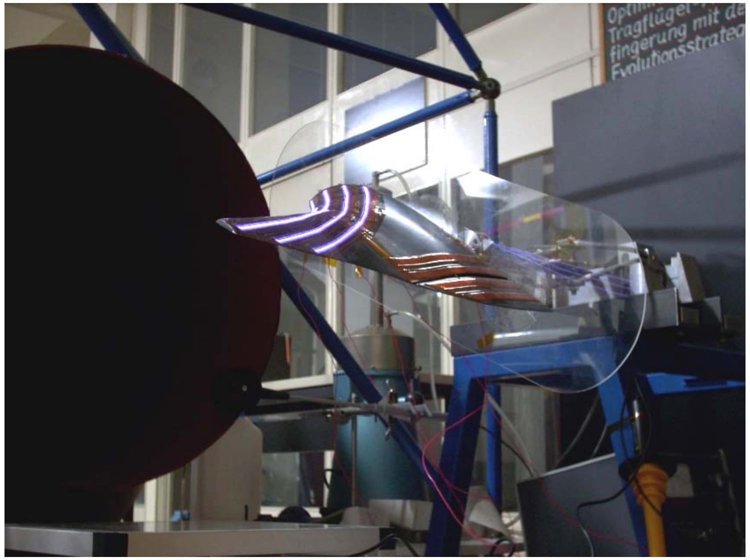
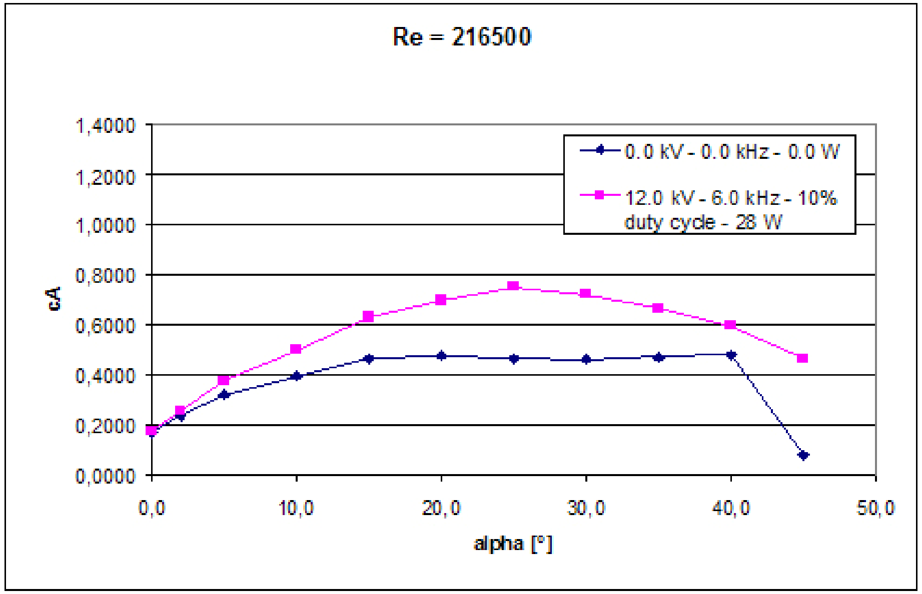
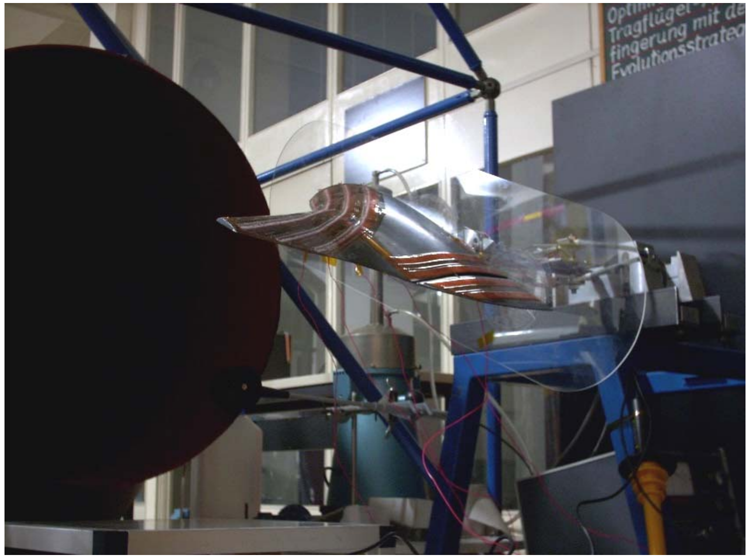


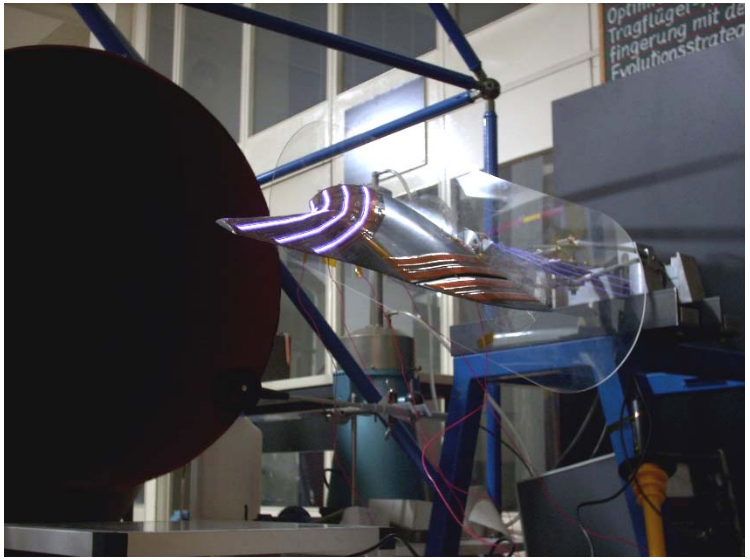


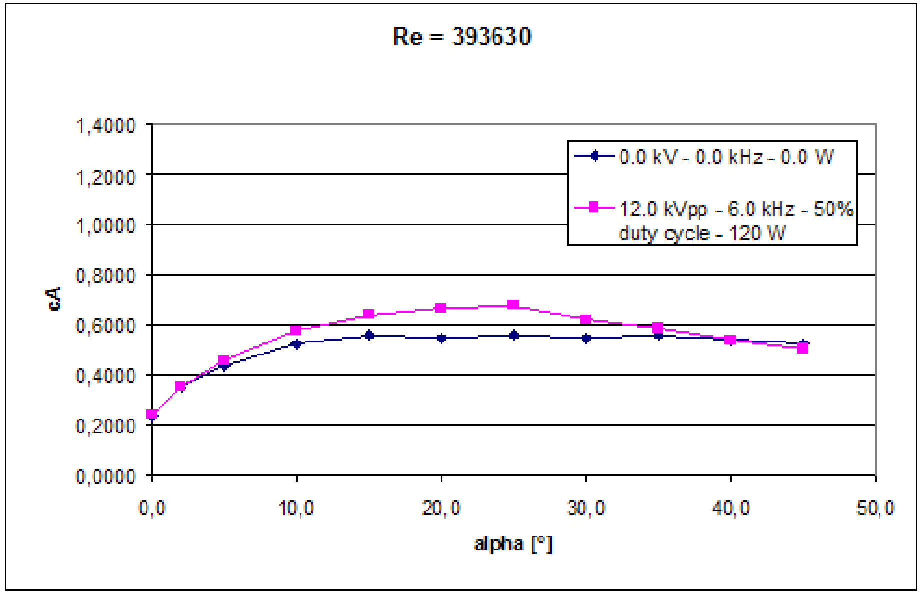


Effect of phased plasma array with four leading edge actuators on half-span wing performance at a root Reynolds number (a) *Re*=36,080 (lift enhanced by max. 300%), (b) *Re*=216,000 (here by max. 60%) and (c) *Re*=393,000 (here by max. 25%)

Half Wing Performance







Effect of phased plasma array with four leading edge actuators on half-span wing performance at a root Reynolds number (a) *Re*=36,080 (lift enhanced by max. 300%), (b) *Re*=216,000 (here by max. 60%) and (c) *Re*=393,000 (here by max. 25%)

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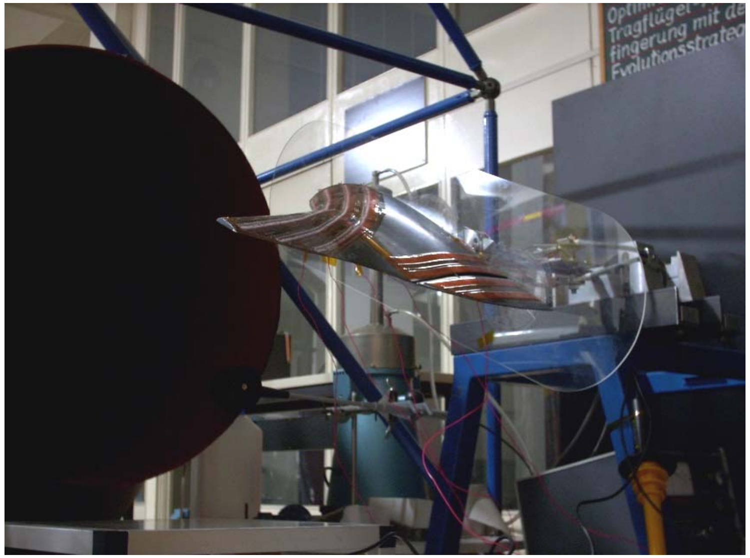
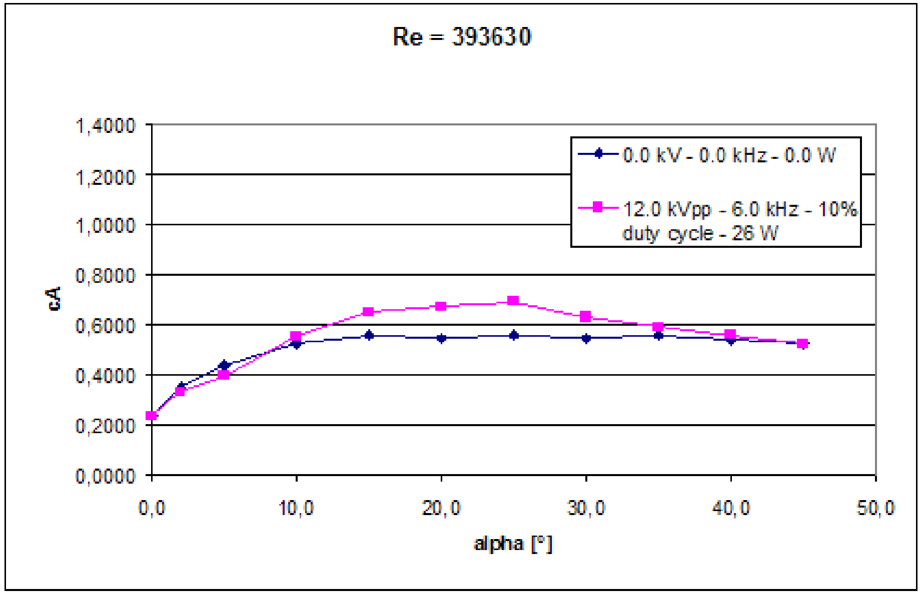
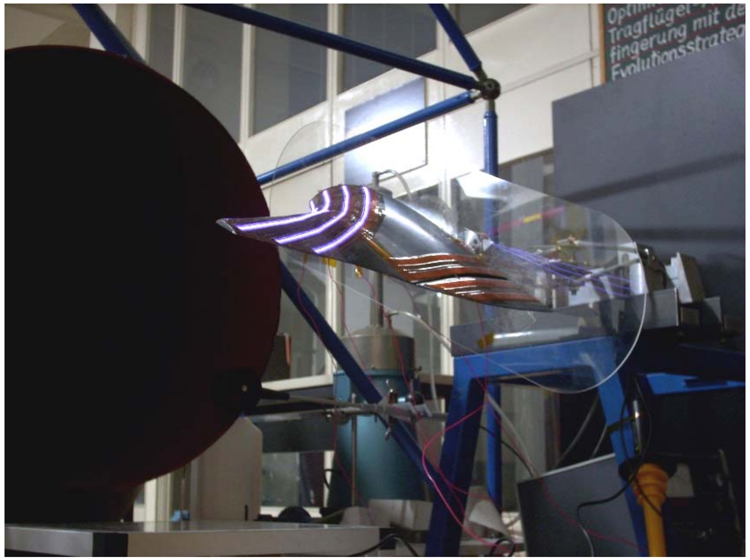
Half Wing Performance

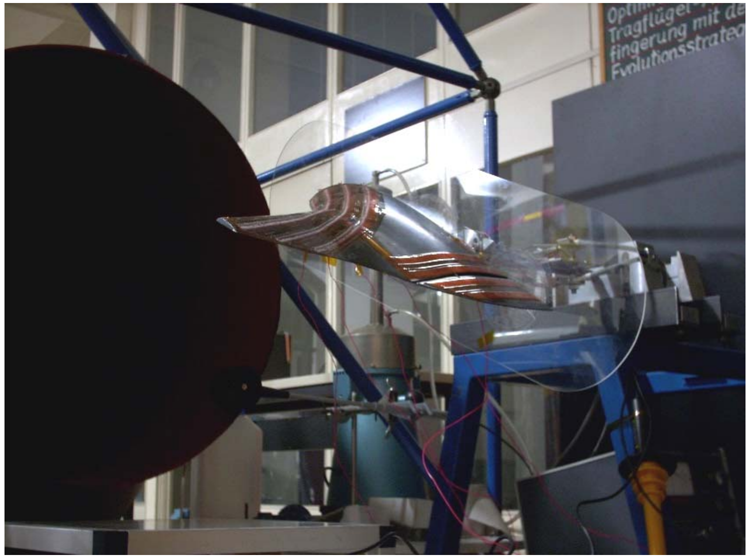


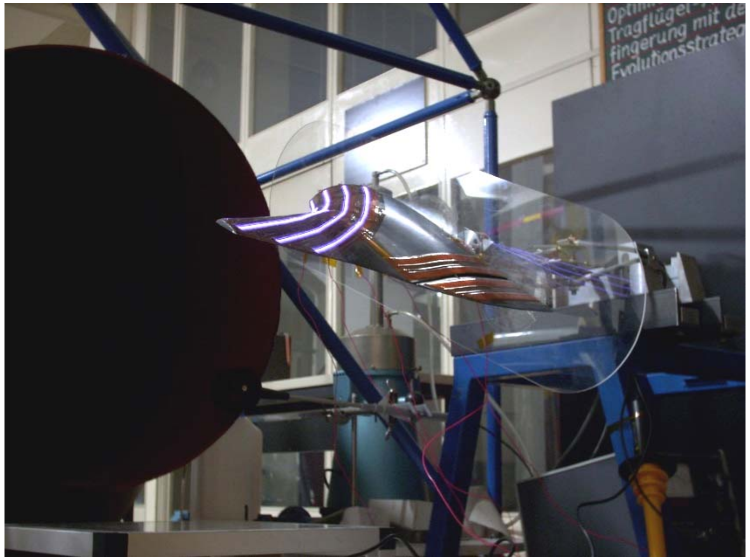


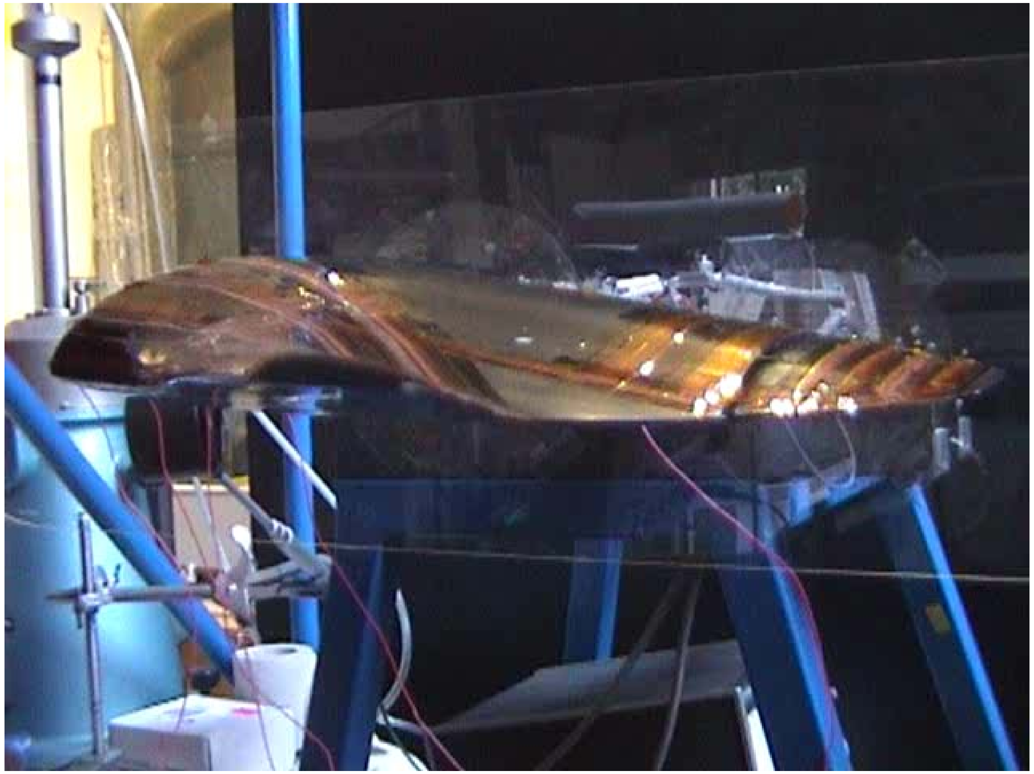


Effect of phased plasma array with four leading edge actuators on half-span wing performance at a root Reynolds number (a) *Re*=36,080 (lift enhanced by max. 300%), (b) *Re*=216,000 (here by max. 60%) and (c) *Re*=393,000 (here by max. 25%)

Half Wing Performance







Effect of phased plasma array with four leading edge actuators on half-span wing performance at a root Reynolds number (a) *Re*=36,080 (lift enhanced by max. 300%), (b) *Re*=216,000 (here by max. 60%) and (c) *Re*=393,000 (here by max. 25%)

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Conclusions and Outlook

- The present investigation considered separation control using single and multi dielectric barrier discharge actuation on an airfoil and half wing models at typical MAV Reynolds numbers.
- Modulating the dielectric barrier discharge actuators at frequencies corresponding to $F^{+}\approx 1$, resulted in improvements to $C_{l,\max}$, which increased with reductions in *Re*. At the low end of the MAV Reynolds number range (*Re*=20,500) modulation increased $C_{l,\max}$ by more than a factor of 2. Hysteresis associated with the baseline airfoil was eliminated.
- Of particular interest from an applications perspective was that performance, measured here by $C_{l,\max}$, increased with decreasing duty cycle, and hence power input, for duty cycles ≥3%. Even lower duty cycles, around 0.66%, were sufficient for effective separation control, corresponding to power inputs on the order of 1.2 milliwatts per centimeter.
- In ongoing experiments, the positive aspects of corona and dielectric barrier discharge plasma actuators are combined in so-called sliding discharge actuators to increase the aerodynamic efficiency of small MAV designs.
- Plasma actuators should also be studied in combination with flapping wing configurations. Why?

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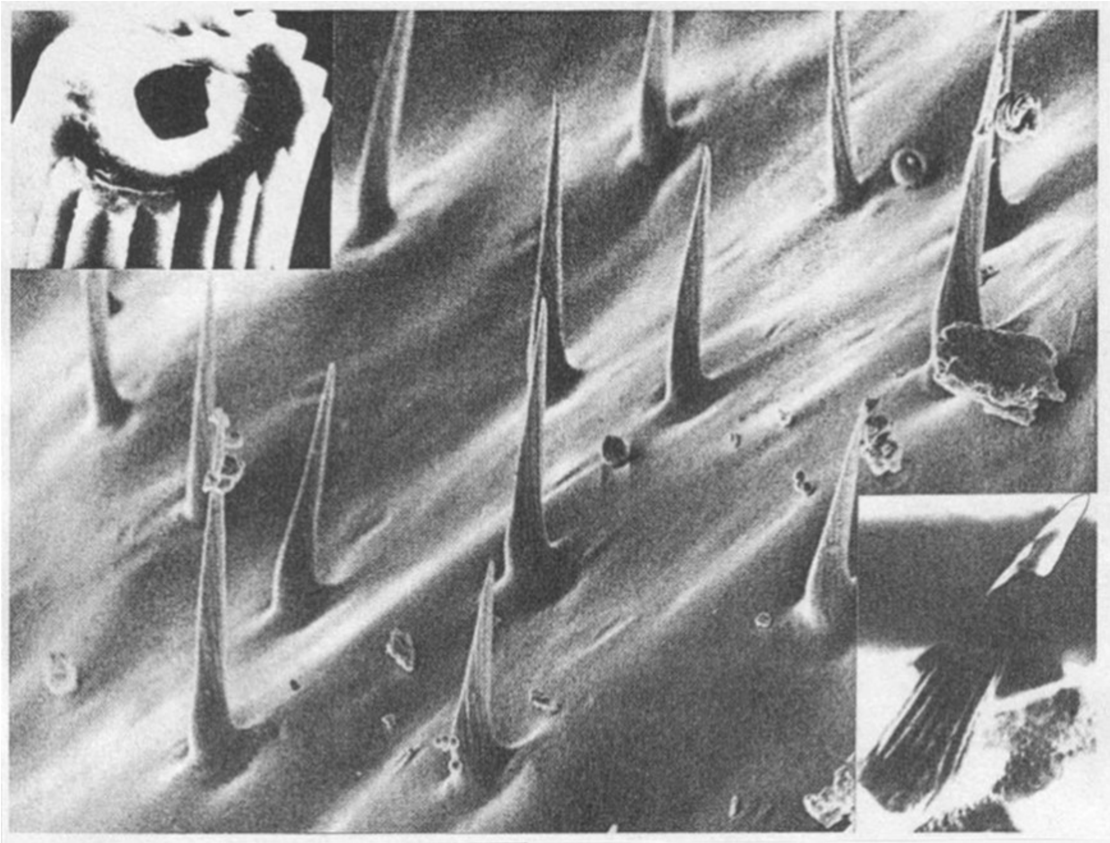
Conclusions

Strange Topography of Bee Wings - Sensors or Supporting Electrokinetic Actuators ?



Warnke, U. (1979) Information Transmission by Means of Electrical Biofields. In *Electromagnetic Bio-Information*, Eds. Popp, F.-A.; Peschka, W., Verlag Urban und Schwarzenberg, München, pp. 55-79.

Stuetzer, O. M. (1961) Apparent Viscosity of a Charged Fluid. *Phys. Fluid* **4** (10), pp. 1226-1231.

Stuetzer, O. M. (1962) Magnetohydrodynamics and Electrohydrodynamics. *Phys. Fluid* **5** (5), pp. 534-544.

Stuetzer, O. M. (1963) *Electrohydrodynamic flow control*. SC-M-69-366, Sandia Corporation, Albuquerque, New Mexico.

Velkoff, H. R. (1962) *Electrofluidmechanics: A Study of Electrokinetic Actions in Fluids*. ASD-TR-61-642. Propulsion Laboratory, Wright-Patterson AFB, Ohio.

What is the Electrokinetic Effect on Vortex Viscosity at Low Reynolds Numbers?

Conclusions

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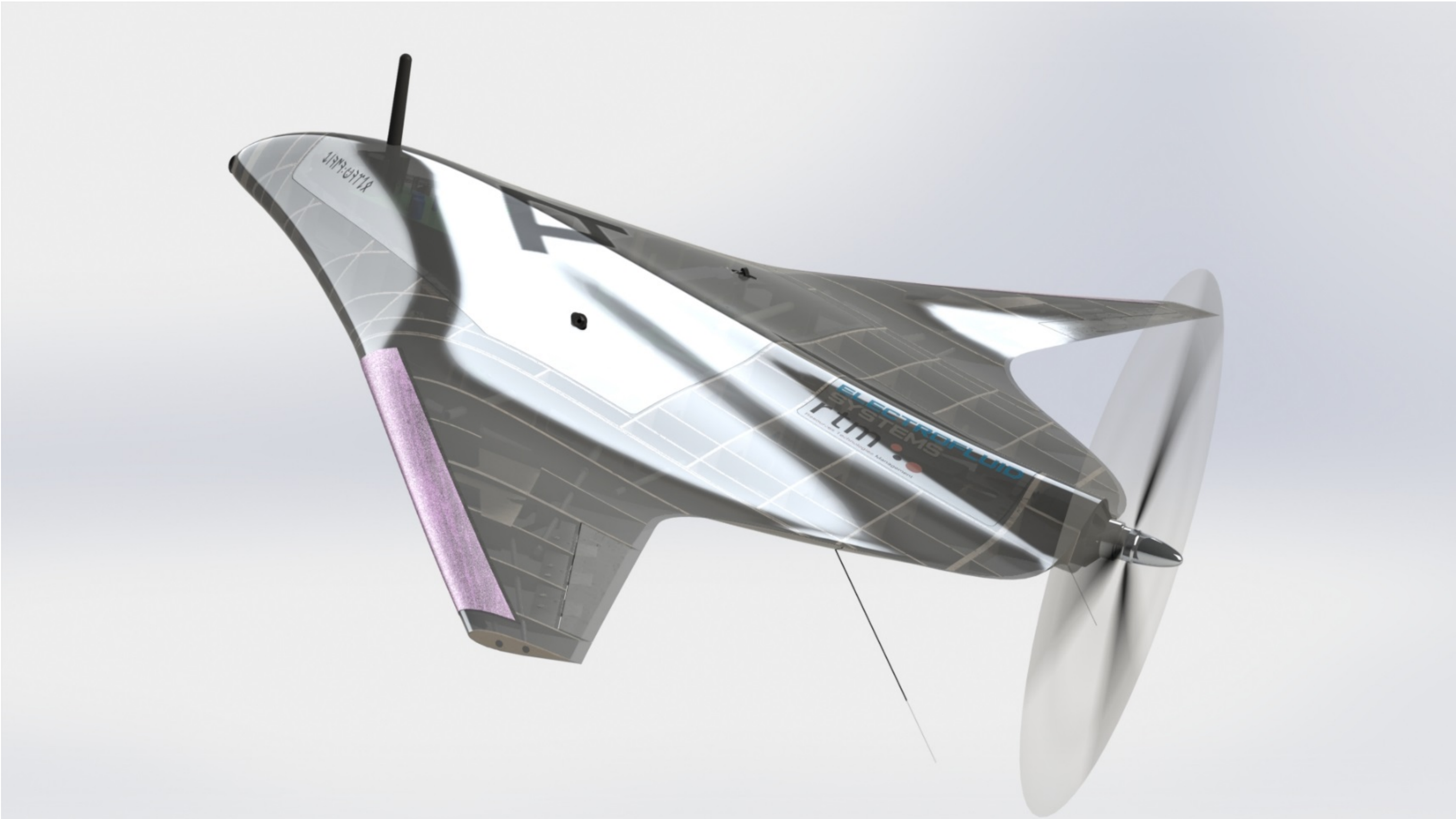
Thank you for your attention!
Any questions?



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