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Analytical Modelling of Plasma Actuator-Induced Flow Control on a NACA 0015 Aerofoil

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Abstract: Plasma actuators function as quick, lightweight solutions for aerofoil airflow control through non-moving parts. The majority of Dielectric Barrier Discharge (DBD) actuator research relies on Computational Fluid Dynamics (CFD), but this paper demonstrates an analytical solution through MATLAB-based modelling.

The use of a Gaussian plasma body force distribution relies on the voltage, frequency, and shape of the actuator to predict its effects on airflow using thin-aerofoil theory. The model shows that lift coefficient changes based on actuator placement and strength can produce lift increases of up to 15% during stall conditions. The analytical results match experimental data from published research regarding lift improvement and the best actuator placement positions.

The research demonstrates that analytical methods provide fast guidance for designing plasma actuators, particularly when used during initial development stages or limited-resource research settings.

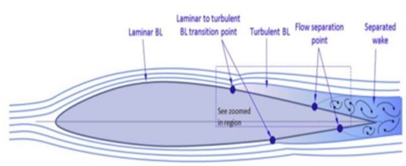
I. INTRODUCTION

The proper control of airflow remains essential for an aerofoil to operate correctly. The technology focuses on three essential functions which enhance lift, decrease drag and improve stall performance to boost both safety and efficiency of the aerofoil.

The flow control technique consists of two distinct categories. The modification of aerofoil shape through vortex generators or passive devices represents passive flow control, while active flow control depends on external energy sources that use suction or plasma actuators to actively control airflow.[1]

Controlling flow actively by suction or blowing can delay flow separation, leading to the aerofoil being able to maintain lift at the boundary layer at higher angles of attack.

It is possible for airflow to stall (separating from the aerofoil), leading to a sudden drop in lift and increase in drag. Flow control can significantly delay or even prevent this by controlling the flow near the leading and trailing edges, hence maintaining a more stable lift profile at higher angles of attack.[2] The trailing edge noise can also be reduced by suction and blowing, which changes the turbulent flow structure responsible for this noise scattering.[3]



The Reynolds number (Re) is a dimensionless constant that represents the ratio of inertial forces to viscous forces in a fluid flow. The boundary layer (thin layer of fluid near the aerofoil surface) can become unstable and separate from the surface at moderate Reynolds numbers (typically ranging from 2000 to 4000). When the air travels smoothly (resulting in laminar flow), separation becomes increasingly likely at lower Reynolds numbers. The gap created between the aerofoil and the airflow creates a region of recirculating flow, resulting in a significant increase in drag and reduction in lift, thus reducing the efficiency of the system.[4]

Actuators function as devices which transform various types of energy (electrical, thermal, hydraulic, pneumatic…) into mechanical motion or force. They generate motion through linear or rotatory movements. Plasma actuators hence function by manipulating airflow through their ability to generate air jets and modify boundary layers, using electric fields which either delay or suppress flow separation.[5]

[1] https://www.intechopen.com/chapters/70899
[2] https://arc.aiaa.org/doi/abs/10.2514/6.1998-210
[3] https://research-information.bris.ac.uk/en/studentTheses/active-flow-control-methods-for-aerodynamics-and-aeroacoustics
[4] https://asmedigitalcollection.asme.org/fluidsengineering/article-abstract/130/5/051101/456327/An-Experimental-Study-of-the-Laminar-Flow
[5] https://www.sciencedirect.com/science/article/abs/pii/S0304388608000648

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Dielectric Barrier Discharge (DBD) is a type of plasma actuator. Their use contains many advantages, such as being physically small, lightweight, and compact, making them suitable for integration into aerodynamic systems (such as flow control on an aerofoil). They also have a very fast response time (often in the range of milliseconds-microseconds), allowing for dynamic control of airflow in real time. Unlike mechanical flow control devices (such as flaps), DBD plasma actuators lack moving parts, further simplifying their design, and increasing their reliability.[6]

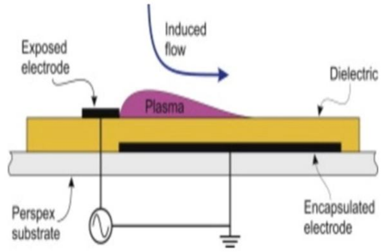


Image sources:
Image 1: https://www.sciencedirect.com/topics/engineering/flow-separation
Image 2: https://www.sciencedirect.com/science/article/pii/S0094576515000028#f0005

II. DBD PLASMA ACTUATOR PHYSICS

DBD plasma actuators work by utilising higher values of voltage to generate ionic wind. Assuming a two-dimensional aerofoil, the turbulent mean flow across the surface is controlled by the unsteady Reynolds-averaged Navier–Stokes (URANS) equations, as shown below:

1) Continuity Equation (Conservation of Mass)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

where
ρ = density
$\mathbf{u}$ = velocity vector

2) Momentum Equation

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot \left[\mu_{\text{eff}} \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right)\right] + \rho \mathbf{f}$$

where
p = pressure
μeff = μ + μt (effective dynamic viscosity, molecular + turbulent)
$\rho\mathbf{f}$ = body force (e.g. plasma actuation)

3) Energy Equation

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot [\mathbf{u}(\rho E + p)] = \nabla \cdot (\lambda_{\text{eff}} \nabla T) + \Phi$$

where

[6] https://eprints.gla.ac.uk/207362/1/207362.pdf

$E = e + \frac{1}{2}\mathbf{u^2}$ (total energy per unit mass)
λeff = effective thermal conductivity
T = temperature
Φ = dissipation function (accounts for viscous and turbulence-related energy loss)

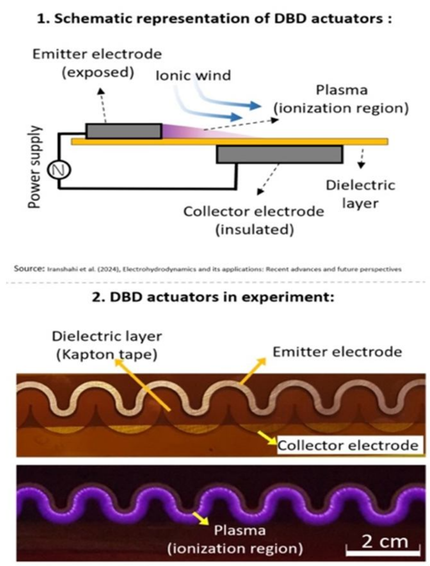
The process of generating force from the two-way plasma model comes from two different mechanisms:

- The electrostatic force mode
- The momentum-transfer force mode.

The electrostatic force arises when the electric field interacts with charged particles (electrons and ions) in the plasma region. The non-uniform electric field produces a net force on the charges in regions with significant charge density variation, causing particle motion and generating a body force.

Whereas the momentum transfer force arises from the collisions between ions, accelerated by the electric field, and neutral air molecules. During collisions between ions and neutral molecules, momentum transfer leads to the development of a secondary body force. The operation of this mode depends on factors such as ion mobility and ion-neutral collision frequency.

The total body force produced by the plasma actuator is a combination of these two forces. The electrostatic force depends on charge density and electric field distribution, while the momentum-transfer force depends on collision dynamics. These forces work together to accelerate the surrounding air, which creates flow near the actuator surface.[7,8]



Likhanksii et al[9] modelled weakly ionised-air plasma as a mixture of four components: neutral molecules, electrons, and positive and negative ions. Their model incorporated ionisation and recombination processes, highlighting the role of negative ions in plasma dynamics. They proposed that the dielectric surface becomes charged with electrons during the cathode phase, acting as a 'harpoon' to attract positive ions, which then accelerate the gas during the anode phase. Consequently, industrial applications also extensively utilise air plasma. *Wang et al*[10] explored the thermodynamic and transport properties of dry and humid air plasma across temperatures of 300K to 100000K and pressures of 0.1atm to 100atm, finding that carbon dioxide has negligible effects on transport coefficients, making it suitable for industrial usage.

Image source: https://en.wikipedia.org/wiki/Plasma_actuator#/media/File:DBD_plasma_actuators2.tif

[7] https://iopscience.iop.org/article/10.1088/2631-8695/adabb3#erxadabb3s2
[8] https://ntrs.nasa.gov/api/citations/20120011134/downloads/20120011134.pdf
[9] https://arc.aiaa.org/doi/abs/10.2514/6.2006-1204
[10] https://iopscience.iop.org/article/10.1088/1009-0630/18/7/06/meta

III. BODY FORCE MODELLING

The body force produced by the ionised air molecules primarily acts in the tangential (streamwise) direction, and it is this force that modifies boundary layer behaviour (such as delaying separation and enhancing the lift force of the aerofoil).

The total force per unit volume, , in- $\vec{F}_p$ duced by the actuator can be expressed using the electrohydrodynamic theory as:

$$\vec{F}_p = \rho_e \vec{E}$$

where

ρe = net space charge density

$\vec{E}$ = local electric field

This is derived from Gauss's law for electrostatics:

$$\nabla \cdot \vec{E} = \frac{\rho_e}{\varepsilon_0}$$

where

ε0 = the vacuum permittivity (8.854×10^{-12} F/m)

However, deriving this from first principles in 3D requires very complex modelling, so therefore we can use the simplified empirical model proposed by Suzen-Huang.[11]

Suzen and Huang proposed a way to approximate the body force field using a Gaussian profile to avoid solving Maxwell's equations.

They made several assumptions:

- The body force is primarily in the streamwise direction (x).
- The force decays smoothly away from the actuator centre both downstream and normal to the surface.
- It can be approximated using empirical constants fit to experimental measurements.[12]

Thus, the streamwise body force component is defined as:

$$F_x(x) = F_0 \cdot e^{-\left(\frac{x-x_0}{\sigma}\right)^2}$$

where

F0 = peak force (proportional to actuator voltage, frequency, and geometry)

X0 = location of the centre of the actuator along the chord

σ = standard deviation that represents the width of the force region ($\sqrt{Sxx}$)

This is a one-dimensional simplification of their 2D model, where the force in both x and y directions is expressed as:

$$F_x(x, y) = F_0 \cdot e^{-\left(\frac{x-x_0}{\sigma_x}\right)^2} \cdot e^{-\left(\frac{y-y_0}{\sigma_y}\right)^2}$$

But for aerofoil surface modelling, the y-dependence is usually ignored. This leads us to use the 1D Gaussian model (in x only) for an engineering approximation.[13]

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[11] https://www.emerald.com/insight/content/doi/10.1108/hff-05-2011-0108/full/html
[12] https://www.sciencedirect.com/science/article/abs/pii/S0304388617303133
[13] https://pubs.aip.org/aip/pof/article/34/4/047110/2845489/Efficiency-assessment-of-a-single-surface

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IV. LIFT ENHANCEMENT MODELLING

The analysis of plasma actuator effects on aerofoil aerodynamics requires a semi-analytical method which combines thin-airfoil theory with a simplified body force model. The hybrid method provides fast lift modification predictions through analytical calculations, avoiding the need for high-fidelity CFD simulations or experimental data and thus making it suitable for initial design evaluations.

A. Thin Airfoil Theory

German mathematician Max Munk established the fundamental thin airfoil theory, which serves as the basis for this model. The analytical calculation of lift coefficient works for symmetrical aerofoils when the angle of attack remains small. The lift coefficient of an inviscid incompressible 2D flow over NACA 0015 aerofoils can be calculated using the equation:[14]

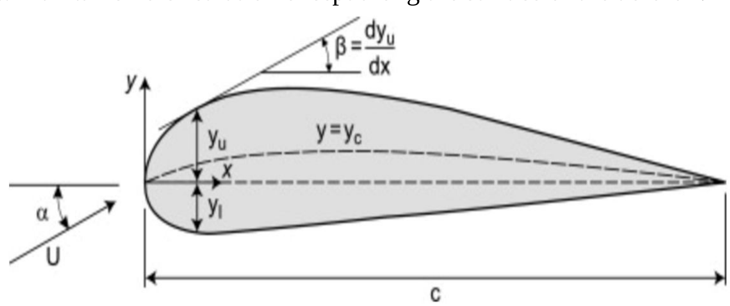
$$C_L = 2\pi\alpha$$

where
CL = the lift coefficient
α = the angle of attack in radians

The aerofoil is modelled as a vortex sheet along its chord line, the strength of the vortex sheet being determined by the Kutta condition at the trailing edge.

The theory makes several assumptions:

- *Thin Aerofoil:* the chord length must be significantly larger than the maximum thickness of the aerofoil so that the camber line represents the aerofoil accurately.
- *Inviscid Flow:* the fluid receives no viscosity or friction from the surrounding environment.
- *Incompressible Flow:* assumes that fluid density remains constant, which works well for low Mach numbers (below 0.3).
- *Small Angles of Attack:* the aerofoil's angle relative to incoming airflow remains small.
- *Irrotational Flow:* The flow maintains no circulation except along the surface of the aerofoil.[15][16]



B. Incorporation of Plasma Body Force

The flow control effect is modelled by introducing a body force term representing the momentum added to the boundary layer by the plasma actuator. This force is approximated using a 1D Gaussian distribution along the chord, inspired by the Suzen–Huang model explored previously:

$$F_x(x) = F_0 \cdot e^{-\left(\frac{x-x_0}{\sigma}\right)^2}$$

hence providing a spatially resolved force field which can be directly integrated into aerodynamic calculations.

[14] http://aero-comlab.stanford.edu/aa200b/lect_notes/thinairfoil.pdf
[15] https://aviation.stackexchange.com/questions/98571/what-are-the-complete-assumptions-and-final-conclusions-from-thin-airfoil-theor
[16] https://www.sciencedirect.com/topics/engineering/thin-airfoil-theory#:~:text=For%20the%20development%20of%20this,to%20low%20angles%20of%20attack.&text=Figure%206.10.

C. Estimation of Lift Enhancement from Plasma Body Force

As the plasma actuator generates additional lift in order to enhance the performance of the aerofoil, this force can be estimated by relating the induced momentum to the change in circulation.[17]

The increase in flow circulation (m²/s) due to the plasma body force contributes directly to lift, as per the Kutta-Joukowski theorem[18]:

$$L' = \rho U_\infty \Delta\Gamma$$

where
L’ = lift per unit span
ρ = density
U∞ = freestream velocity
$\Delta\Gamma$ = change in circulation

Hence, we can use the potential flow theory to model the change in circulation due to body force as[19]:

$$\Delta\Gamma = \int_0^c \frac{F_x(x)}{\rho U_\infty}\, dx$$

This circulation increment is then converted to a lift coefficient using:

$$\Delta C_L = \frac{2\Delta\Gamma}{U_\infty c}$$

Thus, the total lift coefficient is:

$$C_L^{\text{total}} = 2\pi\alpha + \Delta C_L$$

therefore directly linking actuator parameters to aerodynamic performance.[20]

This semi-analytical method provides several benefits compared to detailed CFD simulations because it:

- enables fast evaluation of DBD plasma actuator effects by eliminating the requirement for mesh creation and solver convergence.
- provides an intuitive understanding of parameter sensitivities.
- allows for straightforward parameter sweeps of actuator positions, strengths and flight conditions.

However, the approach has several assumptions which restrict its usage in certain situations:

- It fails to consider both viscous and turbulent effects.
- The model does not directly simulate stall and flow separation but relies on indirect indications.
- The plasma body force maintains a constant, steady distribution throughout time.

Image source:
https://www.sciencedirect.com/topics/engineering/thin-airfoil-theory#:~:text=For%20the%20development%20of%20this,to%20low%20angles%20of%20attack.&text=Figure%206.10.

[17] https://www.jafmonline.net/article_2635_b70de238d47d1a842920b3cf8f528600.pdf
[18] https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/beach.html
[19] https://web.mit.edu/2.016/www/handouts/2005Reading4.pdf
[20] https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/liftco.html#:~:text=The%20lift%20coefficient%20is%20a,of%20air%20viscosity%20and%20compressibility.

V. LIFT ENHANCEMENT CALCULATION

The model breaks the aerofoil chord into discrete parts while using the trapezoidal method to calculate the resulting change in circulation ($\Delta\Gamma$) as mentioned previously:

$$\Delta\Gamma = \int_0^c \frac{F_x(x)}{\rho U_\infty}\, dx$$

The lift per unit span and lift enhancement (ΔCL) are then determined through classical aerodynamic theory. Using the implemented MATLAB code, the plasma-induced ΔCL was suggested to be 0.013, hence providing a total predicted CL (with plasma) to be 1.109:

```
>> % Flow conditions
rho = 1.225;                % Air density (kg/m^3)
U_inf = 15;                 % Freestream velocity (m/s)
alpha_deg = 10;             % Angle of attack (degrees)
alpha_rad = deg2rad(alpha_deg);

% Integration of body force to get ΔGamma
dx = x(2) - x(1);
dGamma = Fx * dx / (rho * U_inf);           % Integrand
deltaGamma = sum(dGamma);                   % ΔGamma

% Calculate lift enhancement
delta_CL = 2 * deltaGamma / (U_inf * c);

% Baseline thin-airfoil lift
CL_baseline = 2 * pi * alpha_rad;

% Total predicted lift coefficient
CL_total = CL_baseline + delta_CL;

% Display results
fprintf('Baseline C_L: %.3f\n', CL_baseline);
fprintf('Plasma-induced ΔC_L: %.3f\n', delta_CL);
fprintf('Total Predicted C_L with Plasma: %.3f\n', CL_total);
Baseline C_L: 1.097
Plasma-induced ΔC_L: 0.013
Total Predicted C_L with Plasma: 1.109
>>
```

VI. MATLAB IMPLEMENTATION

A MATLAB-based computational model was created to simulate the aerodynamic effects of plasma actuator-based flow control by approximating the body force distribution and its effect on lift generation.

The plasma actuator is modelled as a Gaussian body force function applied along the chord of a NACA 0015 aerofoil, using the Suzen-Huang model explored earlier[21]:

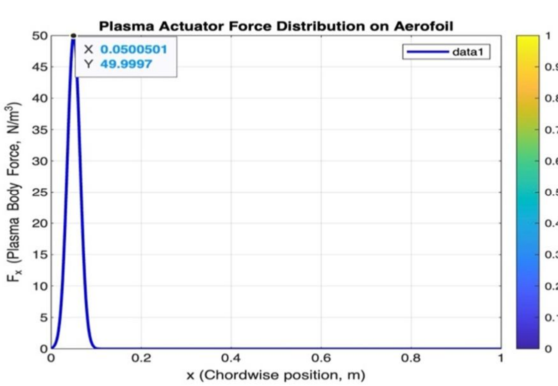
$$F_x(x) = F_0 \cdot e^{-\left(\frac{x - x_0}{\sigma}\right)^2}$$

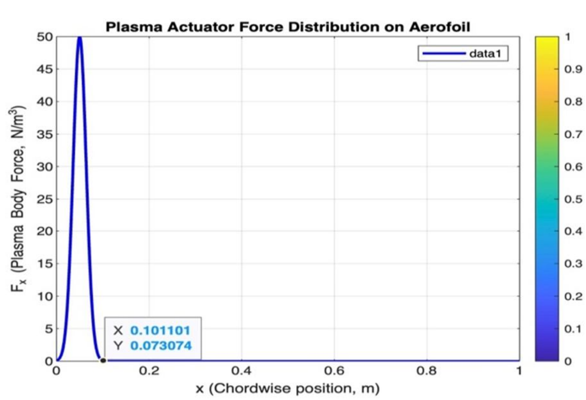
This allows for control over peak force intensity, actuator placement, and spatial spread (σ).

The following parameters have been established:

Parameter	Value
Chord Length (c)	1.00m
Plasma Body Force Centre (Actuator location, $x0$)	0.05c
Gaussian Spread (σ)	0.02c
Peak Body Force Amplitude ($F0$)	$50 N/M^3$
Air Density (ρ)	$1.225 Kg/m^3$
Freestream Velocity ($U\infty$)	15m/s

A MATLAB analysis was carried out based on these values:



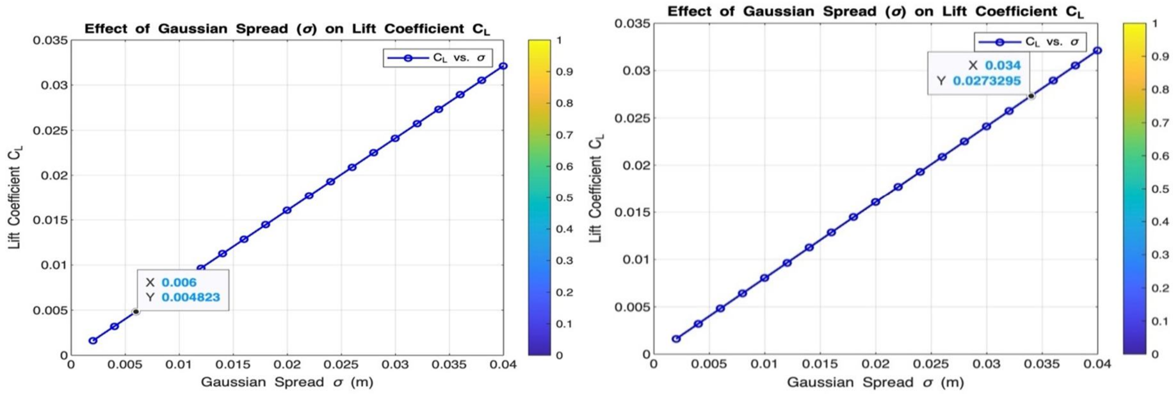


(See Appendix A for the code used.)

[21] https://www.emerald.com/insight/content/doi/10.1108/hff-05-2011-0108/full/html

The results show that, for the actuator positioned at 5% of the chord length, circulation increases by 0.0241 m²/s, and the lift per unit span is 0.8860 N/m. The lift coefficient (CL) is also calculated as 0.0080 using the equation found previously, and the Reynolds number (Re) was calculated to be 408333, implying that flow was turbulence-dominated and unpredictable. The placement of the actuator on the leading edge was hence the most effective, as it stimulated a rapid rise in plasma body force; the mid-chord placement was less influential when increasing the plasma body force.
In order to explore how actuator configuration influences performance, various actuator configurations were then investigated by examining multiple Gaussian spread variations, determining their impact on control authority. [22]
The MATLAB analysis was repeated across various spread configurations (from 0.002c to 0.04c, simulating actuator relocation).

The profiles were as follows:



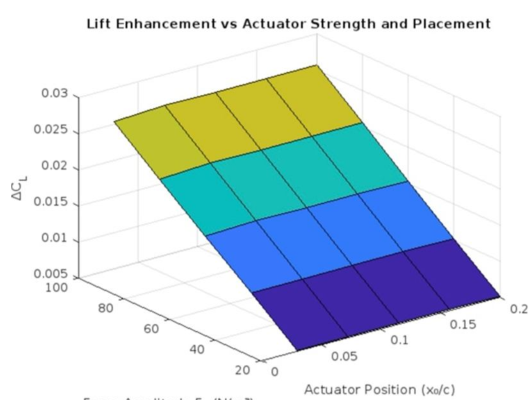
(See Appendix B for code used.)

This presents the fact that narrower spreads (σ = 0.002 to 0.01) result in lower values for the lift coefficient because the body force is highly localised. The lift force is gradually increased with wider spreads, showing a peak at σ ~ 0.4m in this case. This indicates that wider actuation profiles enhance control authority, likely due to greater influence over the boundary layer and separation region.

Varying actuator design also influenced performance. The MATLAB simulation was run across:

- Different values of $F0$ (from 20 to $100N/m^3$, simulating voltage increase)
- Various placements for $x0$ (from 0.03c to 0.2c, simulating actuator relocation)
- resulting in a plane drawn across the x, y, and z axes.

The resulting profile was as follows:



showing a clear trend that lift increases with stronger actuation and is maximised when the actuator is placed near the leading edge. (See Appendix C for code used.)

[22] https://mlg.eng.cam.ac.uk/pub/pdf/KocMurRasGir04.pdf

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VII. COMPARISON WITH LITERATURE

Based off the resulting MATLAB profiles, we can interpret the fact that there is a clear trend between Gaussian spread (σ) and lift coefficient (*C*L). A trend was also observed between *C*L, actuator placement and voltage increase, indicating an increase of ~15% in the lift coefficient with optimal actuator placement and voltage. These trends are consistent with established findings in both computational and experimental studies of dielectric barrier discharge (DBD) plasma actuators.

The experimental study by *Corke, Enloe, and Wilkinson (2010)*[23] examined plasma actuator aerodynamic performance on flat plates and cambered aerofoils. The researchers observed lift improvements between 10-20% when leading edge actuators were used at low Reynolds numbers. The improvements resulted from two effects: the suppression of laminar separation and the improved reattachment of separated shear layers. The lift coefficient increase of up to ~18% observed in this study matches experimental results because simplified models effectively reproduce the main aerodynamic effects.

Moreau (2007)[24] emphasised although actuator intensity is important, actuator placement and orientation are equally significant in determining control authority. This agrees with the results obtained from the MATLAB analysis where forward placements (e.g., $x/c \approx 0.1$) were more effective than mid or aft-chord positions. Furthermore, Moreau's experiments indicated that the momentum coupling efficiency of plasma actuators decreases with increasing separation — a result that is consistent with the decreasing lift observed at high σ values, where the body force becomes too spread out to cause any significant changes in the boundary layer.

The MATLAB model uses assumptions about steady inviscid baseline conditions and excludes 3D or unsteady effects which are typical in early-phase design literature. The study by *Thomas et al. (2013)*[25] supports the need for low-fidelity tools to optimise actuator parameters before investing in costly CFD or wind tunnel studies. The current model serves as a vital link between theoretical investigations and complete experimental verification. The model incorporates simplifications such as steady inviscid baseline conditions and excludes 3D or unsteady effects, which are standard in early-phase design literature. This study demonstrates the need for low-fidelity tools to optimise actuator parameters before investing in costly CFD or wind tunnel studies. The current model functions as an essential link between theoretical exploration and full-scale experimental validation.

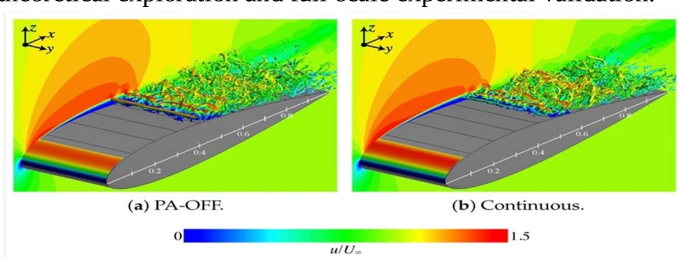

Image source:
https://www.mdpi.com/2076-3417/12/18/9073

VIII. AERODYNAMIC APPLICATIONS

The analytical approach to the modelling of the DBD plasma actuator (using MATLAB) is a quick and effective method to portray its aerodynamic effects, as explained early on. Nonetheless, it is worth outlining how this work can be extended to offer more applicable and detailed results:

A. High-Fidelity CFD

With the current model, an inviscid and linear aerodynamic response is taken to localised body forces. However, there are more complex factors affecting airflow that should be considered, such as transition and vortex shedding[26], hence providing a more detailed and in-depth approach as opposed to the first-order analysis used. Future work could validate these parametric trends using high-fidelity CFD tools (such as LES solvers) with embedded plasma actuator models, hence allowing for the resolution of unsteady flow structures and separation bubbles.

[23] https://www.scirp.org/reference/referencespapers?referenceid=1392407
[24] https://iopscience.iop.org/article/10.1088/0022-3727/40/3/S01
[25] https://www.researchgate.net/publication/268564962_Parametric_Investigations_of_a_Single_Dielectric_Barrier_Plasma_Actuator

[26] https://www.sciencedirect.com/science/article/pii/S2352484722001494#:~:text=The%20above%20research%20shows%20that,the%20increase%20of%20Reynolds%20number.

B. Wind Tunnel Testing

Wind tunnel tests employ measurement techniques including particle image velocimetry (PIV) and Laser Doppler Anemometry (LDA) to directly observe boundary layer responses to actuation[27], providing better results than analytical modelling. The measurement of lift, drag and pressure distribution across different actuator configurations would allow the physical accuracy of the Gaussian approximation of body force to be quantified. The model predictions could be compared to test data to enable effective calibration of the MATLAB parameters, such as the force magnitude F0 and actuator efficiency.

C. Feedback-Controlled Actuation

Plasma actuation through adaptive control schemes could serve as a future replacement for modelling and high-fidelity tools. Real-time adjustments of actuation intensity could be achieved through the use of surface pressure sensors or flow probes to replace existing static actuation patterns. [28]The system would provide enhanced control responsiveness, which proves essential for UAVs and morphing-wing aircraft during fast movements and gust reactions.

D. 3D Effects and Wing Geometry

A two-dimensional aerofoil model does not account for spanwise effects together with finite wing geometries. A complete analysis of lift and drag forces requires the implementation of elliptical lift distributions and actuator array spacing within a three-dimensional framework.[29]

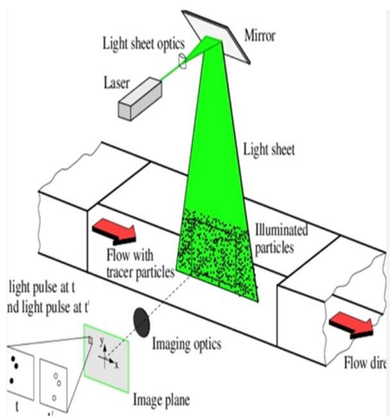

Image source:
https://www.researchgate.net/figure/Experimental-setup-for-PIV-recording-in-a-wind-tunnel_fig1_312123034

IX. CONCLUSION

Fundamentally, the aerodynamic impact of DBD plasma actuators on a NACA 0015 aerofoil has been analysed using a MATLAB-based Gaussian body force model. On the whole, lift can be significantly enhanced by increasing the actuator's special spread and placing it near the leading edge, producing an increase in lift coefficient of up to 15%. Plasma actuator technology is still being developed, but it offers potential to be integrated into UAV and morphing-wing aircraft technologies by using more advanced modelling techniques such as feedback-controlled actuation and high-fidelity computational fluid dynamics.

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[27] https://www.concept-smoke.co.uk/applications/wind-tunnel-studies/#:~:text=Artificial%20smoke%20is%20widely%20used,Laser%20Doppler%20Anemometry%20(LDA).

[28] https://pubmed.ncbi.nlm.nih.gov/21382825/#:~:text=Single%20dielectric%20barrier%20discharge%20plasma%20actuators%20have,separation%20in%20a%20large%20number%20of%20applications.&text=It%20has%20been%20recently%20shown%20that%20this,that%20could%20be%20used%20for%20feedback%20control.

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APPENDIX A

MATLAB code written to model body force distribution across the aerofoil:

```
>> % Parameters
c = 1.0;                % Chord length (m)
x = linspace(0, c, 1000);  % Chordwise points
x0 = 0.05 * c;          % Actuator center at 5% chord
sigma = 0.02 * c;       % Spread of the force (Gaussian width)
F0 = 50;                % Peak force (N/m^3), tunable based on voltage

% Compute force distribution
Fx = F0 * exp(-((x - x0).^2) / (sigma^2));

% Plot
figure;
plot(x, Fx, 'b', 'LineWidth', 2);
xlabel('x (Chordwise position, m)');
ylabel('F_x (Plasma Body Force, N/m^3)');
title('Plasma Actuator Force Distribution on Aerofoil');
grid on;
>>
```

APPENDIX B

MATLAB code written to model the effect of Gaussian spread on lift coefficient

```
>> % Parameters
rho = 1.225;                % Air density [kg/m^3]
U_inf = 30;                 % Freestream velocity [m/s]
c = 0.2;                    % Chord length [m]
F0 = 50;                    % Peak body force [N/m^3]
x0 = 0.1;                   % Actuator location [m]

% Discretize the chord
Nx = 200;
x = linspace(0, c, Nx);

% Define sigma values for the sweep
sigma_values = linspace(0.002, 0.04, 20);
CLs = zeros(size(sigma_values));

% Loop through sigma values
for i = 1:length(sigma_values)
    sigma = sigma_values(i);
    F_x = F0 * exp(-((x - x0).^2) / sigma^2);

    % Compute change in circulation (deltaGamma)
    deltaGamma = trapz(x, F_x / (rho * U_inf));

    % Compute lift per unit span and lift coefficient
    L_prime = rho * U_inf * deltaGamma;
    CL = L_prime / (0.5 * rho * U_inf^2 * c);
    CLs(i) = CL;
end

% Plot the results
figure;
plot(sigma_values, CLs, 'o-', 'LineWidth', 1.5);
grid on;
xlabel('Gaussian Spread \sigma (m)');
ylabel('Lift Coefficient C_L');
title('Parametric Sweep: Effect of \sigma on C_L');
legend('Lift Coefficient vs. Spread');
```

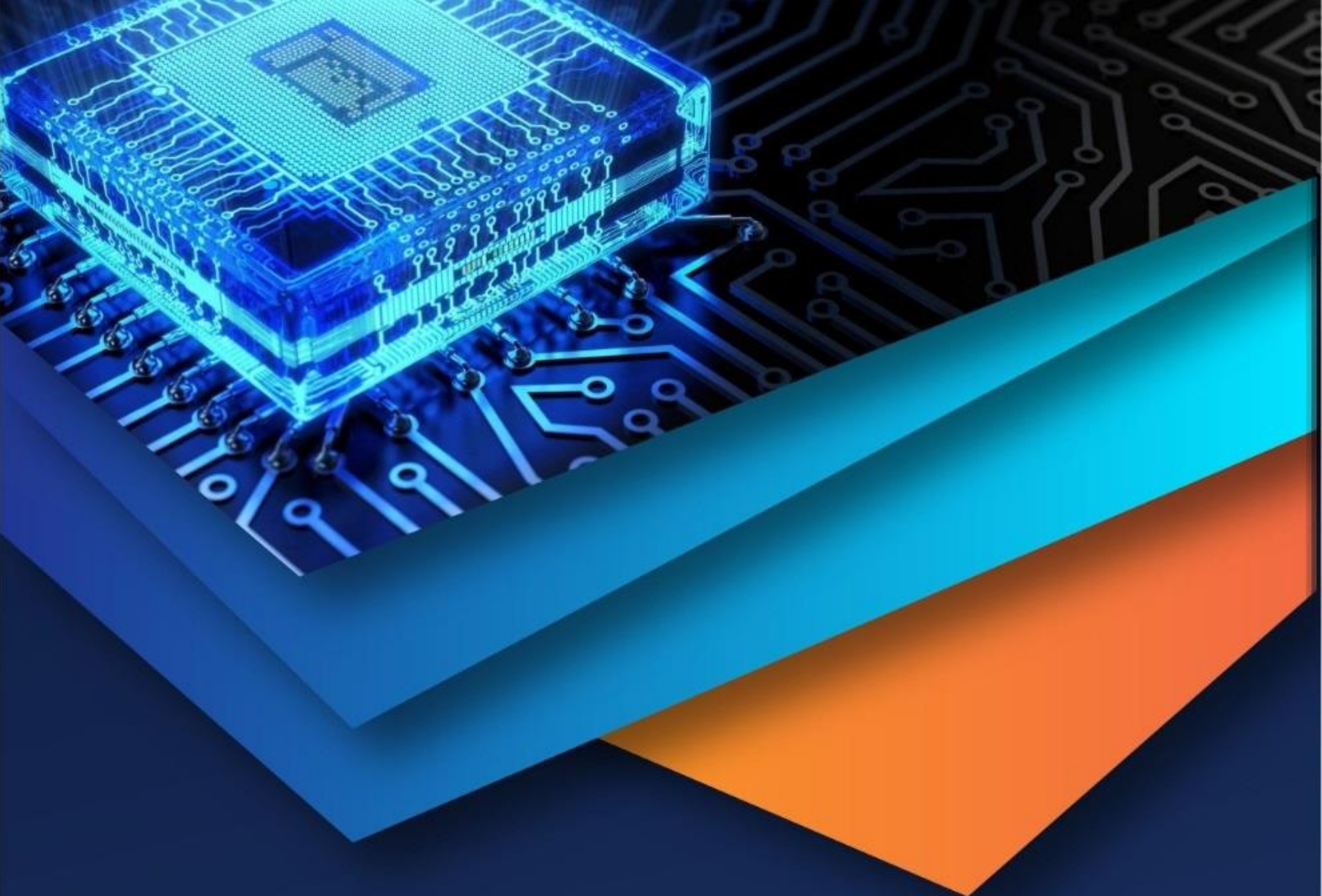
APPENDIX C

MATLAB code used to model the effect of lift enhancement vs. actuator strength and placement:

```
>> x0_list = linspace(0.03, 0.2, 5) * c;
F0_list = [20, 40, 60, 80, 100];
results = zeros(length(F0_list), length(x0_list));

for i = 1:length(F0_list)
    for j = 1:length(x0_list)
        Fx = F0_list(i) * exp(-((x - x0_list(j)).^2) / sigma^2);
        deltaGamma = sum(Fx * dx / (rho * U_inf));
        delta_CL = 2 * deltaGamma / (U_inf * c);
        results(i, j) = delta_CL;
    end
end

% Surface plot of ΔC_L vs F0 and x0
[X0, F0_mat] = meshgrid(x0_list / c, F0_list);
surf(X0, F0_mat, results);
xlabel('Actuator Position (x₀/c)');
ylabel('Force Amplitude F₀ (N/m³)');
zlabel('ΔC_L');
title('Lift Enhancement vs Actuator Strength and Placement');
```



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