DRAG REDUCTION IN AIRCRAFT WINGS USING DIELECTRIC BARRIER DISCHARGE (DBD) PLASMA FLOW CONTROL ACTUATORS

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Abstract. The year 2050 flightpath set by the Advisory Council for Aeronautics Research in Europe (ACARE), has established ambitious goals regarding the reduction of pollutant emissions produced by the aircraft aeroengines. In order to achieve these environmental targets for aviation, a reduction of CO_2 and NO_x emissions is obligatory, which is directly related to the reduction of the specific fuel consumption (SFC) of aeroengines. Low SFC values can be partially achieved by low demands on thrust and by consequence by low aircraft aerodynamic drag. The aerodynamic drag can be reduced by various active and passive flow control techniques. An innovative and promising active flow control technique towards the aerodynamic drag reduction is the use of plasma actuators. In the current study, the positive effect of a particular plasma actuator (which is referred in the literature as the dielectric barrier discharge (DBD) actuator) on controlling the flow on wings and hence, reducing the aerodynamic drag, is numerically investigated. The results of the study show that, at low speed conditions, such as during the approach and landing flight segments, the aircraft's total drag can be reduced up to 5%. It is concluded that the use of DBD plasma actuators for flow control on the lifting surfaces of an aircraft has a potential to reducing the total aerodynamic drag of an aircraft. As a consequence, this has a direct impact on the aeroengine SFC which in turn can lead to a 5% pollutants emissions reduction.

Keywords: Drag reduction, Plasma actuators, Dielectric Barrier Discharge, Active flow control, Pollutants emissions reduction

INTRODUCTION

The goals that have been set by the Advisory Council for Aeronautics Research in Europe (ACARE) regarding to the NO_x and CO_2 pollutant emissions, lead to a demand for more aerodynamic efficient aircraft, with lower specific fuel consumption (SFC) values. These goals can be achieved by reducing the required thrust, and consequently, by reducing aircraft aerodynamic drag (Caruana 2010). Drag reduction can be managed by using more efficient wing and fuselage configurations (Abbas et al. 2013) or by means of active and passive flow control techniques (Bushnell 2003).

Such an active flow control mechanism is the Dielectric Barrier Discharge (DBD) plasma actuator. The DBD plasma actuator consists of two electrodes that are separated by a dielectric material. High voltage is applied on the electrodes, resulting in a non-thermal plasma sheet as shown in fig.1. This causes an ionic wind, similar to a wall jet into the boundary layer, thus it is able to modify its properties.

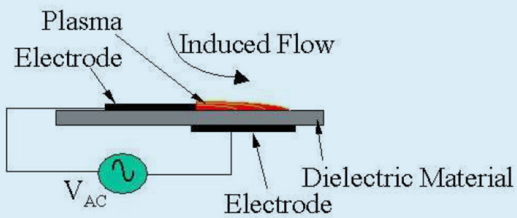

Figure 1. DBD plasma actuator configuration, figure from (Suzen et al. 2005).

The current work focuses on the effect of the DBD plasma actuator on a NACA 0012 lift and drag coefficients. A 2D Computational Fluid Dynamic analysis was carried out using the ANSYS FLUENT commercial computational fluid dynamics (CFD) software (ANSYS, Release 15) with the use of user defined functions (UDFs).

METHODOLOGY

The modelling of the DBD plasma actuator and the coupling of the plasma force with the momentum equations is carried-out using the mathematical model of (Suzen et al. 2005). This model introduces two new transport equations in order to model the resulting jet-like body force that acts on the fluid. These equations are solved in combination with the Reynolds Averaged Navier-Stokes (RANS). The resulting plasma body force interacts with the momentum equations as an additional body force source term in the RANS equations. Finally, for modelling turbulence the SST k-ω model (Menter 1994) was implemented. The corresponding equations are briefly presented below. Namely, the induced plasma body-force (eq.1), the transport equation of the net charge density ρ_c (eq.2), the transport equation of the external electric field φ (eq.3) and the momentum transport equations (eq.4). Details regarding the implementation of the adopted DBD model can be found in (Suzen et al. 2005).

The

$$\vec{f}_B = \rho_c(-\nabla\varphi) \quad (1)$$

$$\frac{\partial}{\partial x_j}\left(\varepsilon_r \frac{\partial \rho_c}{\partial x_j}\right) = \frac{\rho_c}{\lambda_d^2} \quad (2)$$

$$\frac{\partial}{\partial x_j}\left(\varepsilon_r \frac{\partial \varphi}{\partial x_j}\right) = 0 \quad (3)$$

$$\frac{\partial \rho \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \rho \bar{U}_i}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right)\right] - \frac{\partial}{\partial x_j}\left(\rho \overline{u_i' u_j'}\right) - \rho_c \frac{\partial \varphi}{\partial x_i} \quad (4)$$

The computational domain which was used for the computations is a structured like C-type mesh with $4x10^5$ number of cells, as shown in fig.2 and is divided in two domains. The main fluid domain that refers to the whole region around the NACA 0012 airfoil, and the plasma actuator solid domain that is the region where the DBD plasma actuator is placed. In the fluid domain the momentum, the turbulence model, the net charge density and the voltage transport equations were solved, while in the sold domain only the voltage transport equation was solved.

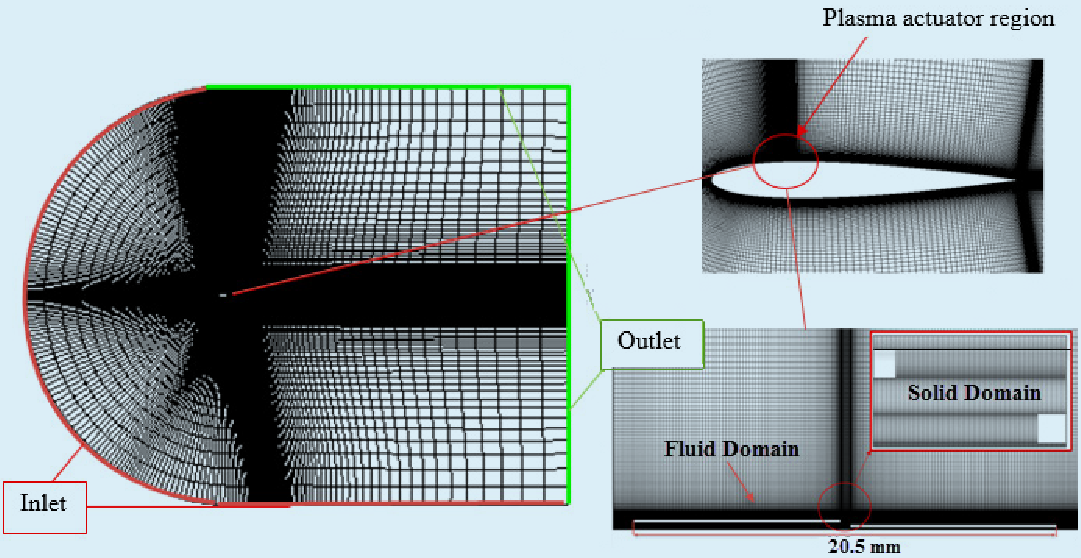

Figure 2. C-type like computational domain and fluid boundary conditions.

RESULTS

The NACA 0012 airfoil has a chord length of 0.5m, and the DBD plasma actuator is placed on the quarter chord of the airfoil where the separation of the flow initiates. Regarding the boundary conditions, the freestream velocity is 20 m/s and the freestream turbulence intensity is about 1%. The applied voltage values on the DBD plasma actuator implemented in the current study are 10 kV and 30 kV.

Figure 3 presents indicative streamlines around the NACA 0012 at 15° angle of attack with and without actuation at 30kV. When the DBD actuator is on, a reduction of the wake thickness is observed, which leads to a drag reduction and lift increase.

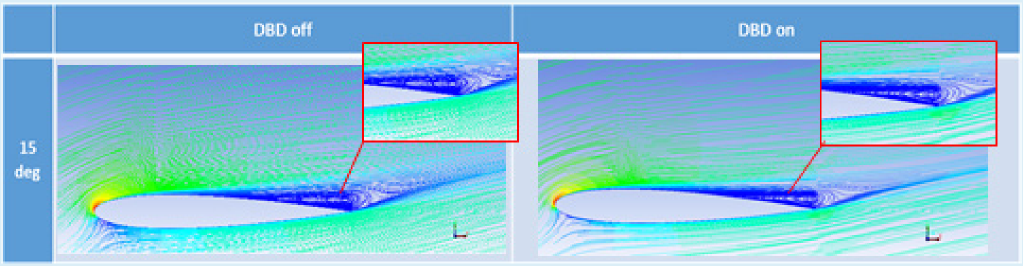

Figure 3. Streamlines around NACA 0012. Left: DBD off. Right: DBD on (30kV).

The results regarding the lift (C_l) and drag (C_d) coefficients distributions as a function of angle of attack (AOA), with DBD actuator on at 10kV and 30kV and DBD off, in comparison to the results of the Xfoil free software (Drela M. 1989) are shown in fig.4. The effect of the DBD actuation for the different voltages at 15° AOA on the lift and drag coefficients are summarized in table 1. It is shown that when the airfoil AOA takes high values, such as 15-16 degrees, where the flow separation and stall occurs, a 10% reduction in C_d and a 4% increase in C_l is observed. The same percentage difference for the aerodynamic coefficients percentage improvement can be also applied in a wing (Raymer 1992).

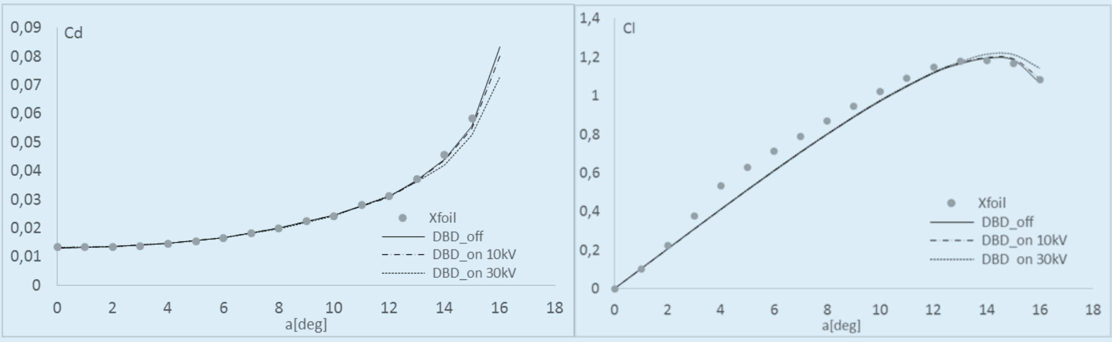

Figure 4. Left: C_d versus angle of attack. Right: C_l versus angle of attack.

Table 1. Lift and drag coefficient values at AOA=15° in different DBD actuator modes

Actuator mode	Applied voltage kV	Cl_{max} @ 15°	Cd @ Cl_{max}
Off	-	1.184	0.57
On	10	1.192	0.55
On	30	1.23	0.52

The Thrust Specific Fuel Consumption (TSFC) is defined in equation (5) (Saravanamuttoo et al. 2001).

It is evident that for an aeroengine with constant TSFC in a specific mission segment where the DBD can have an effect, a reduction in drag and consequently in thrust leads to a proportional reduction in the required fuel mass.

$$TSFC = \frac{\dot{m}_f}{T} \qquad (5)$$

Based on (Raymer. 1992) the percentage of the wing drag in the landing and take-off segments of flight is about 45 - 50% of the overall aircraft drag during these segments. So a 10% drag reduction, which has the potential to be achieved by the DBD plasma actuators, leads to a 5% reduction of the total aircraft drag during take-off and landing.

For a typical aeroengine the NO_x and CO_2 pollutant emissions reduction is proportional to aerodynamic drag reduction, (Kyprianidis et al. 2015) and (Ashok et al. 2014). As a result, a 5% NO_x (based on NO_x Emissions Index (g NO_x /kg fuel) and 5% CO_2 reduction is expected when an equivalent percentage of drag reduction is achieved.

Furthermore, the DBD plasma actuators can be used in order to reduce the skin friction drag of the other aircraft components apart from wings, such as the fuselage and the empennage, in the cruise segment of flight. Additionally, DBDs can be used to reduce other forms of drag during cruise (i.e. interference drag, induced drag) and even change the boundary layer characteristics over the wings (transition control) in favour of reducing fuel consumption and pollutant emissions. Finally, the DBD active flow control system can also contribute in the versatility of the aircraft, by providing the option of modifying the aerodynamic characteristics and the aircraft manoeuvrability during flight. Based on the low power and low weight requirements (Kriegseis et al. 2011), the low construction complexity, and the lack of mechanical parts (Moreau 2007), this innovative active flow control technique is a promising candidate for future aircraft active flow control basically in the low speed segments of the aircraft flight.

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