Experimental and numerical study of boundary layer transition control over an airfoil using a DBD plasma actuator

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Abstract

In this paper, the effects of Dielectric Barrier Discharge (DBD) actuation on the boundary layer transition have been studied on an ONERA-D airfoil both experimentally and numerically. The experiment has been conducted in a subsonic wind tunnel for freestream velocities up to 24 m/s and for two different actuator locations. Hot-wire probing enabled to quantify the influence of the ionic wind on the boundary layer mean velocity profiles and on the resulting transition shifts. The maximum measured transition delay was about 6% of chord. These measurements served as references to establish a numerical model of the body force induced by a plasma actuator. Linear stability analysis is then applied to the mean flow induced by the body force model and compared to the measured mean velocity profiles.

Keywords: Plasma actuator ; dielectric barrier discharge ; transition control

1. Introduction

One possible way to reduce aircraft fuel consumption is to delay boundary layer transition on wings in order to reduce skin friction drag. Stabilization of the boundary layer by modification of the mean velocity profiles is a possible approach to achieve this aim and can be performed by numerous ways. Among them, an interesting one is plasma actuation because of its easy implementation on a surface, the light weight of the actuators and because of their input energy which is electricity and allows easy control and modulation of the actuators.

In this work, the actuation is performed using a DBD plasma actuator. This type of actuator is constituted of two electrodes stuck on each face of a dielectric material. When an alternative high voltage is applied between the electrodes, the ambient air is ionized. The charged particles drift under the effect of the electric field and create a body force tangential to the wall (the ionic wind), which is used in this case for transition control. Experiments of transition delay have been successfully conducted on a flat plate and on a profile for two dimensional configurations and low freestream velocities, around 10 m/s. Other experiments have been recently realized on a flat plate for velocities of...
about 20 m/s. The experiments presented in this paper were focused on delaying the boundary layer transition over an unswept ONERA-D airfoil for upstream velocities up to 24 m/s.

From a numerical point of view, several models have been developed for the body force field generated by a DBD plasma actuator. They can be classified in two main categories: the phenomenological ones which are based on the physics and chemistry of plasma\textsuperscript{5–9} and the empirical models generally based on velocity measurements in the vicinity of plasma actuator in quiescent air\textsuperscript{10–12}. As one body force model only suits well to one actuator geometry a first empirical model, corresponding to the present experiment, has been developed and implemented in the ONERA in-house boundary layer code 3C3D.

In this paper, an experimental study of the effect of DBD actuators on the boundary layer depending on their position and electrical parameters is first presented. The obtained measurement are used to define the empirical model. Stability computation performed on both numerical and experimental velocity profiles are then analysed.

2. Experimental study

2.1. Experimental set-up

The experimental study has been conducted in the TRIN 1 subsonic open-return research wind tunnel located at ONERA Toulouse. It features a low turbulence level ($0.5 \cdot 10^{-3} < T_u < 2 \cdot 10^{-3}$) for a freestream velocity range of $10 < U_\infty < 80$ m/s), which makes it well-suited for laminarity and transition studies. The wing model has an ONERA-D symmetric profile whose chord measures 35 cm set at an angle of attack $\text{AoA} = 1.5^\circ$ in an unswept configuration. The model is equipped with 15 pressure taps on the suction side in order to measure the pressure distribution.

A 5 mm-thick dielectric insert made of Lab 850 allowed the model to be outfitted by the desired number of DBD actuators between the leading edge and 40% of chord (Fig. 1 a). The air-exposed electrode was 12 mm width chordwise and the grounded one 21 mm. Both electrodes, made of copper tape, were $L = 25$ cm long spanwise and 50 μm thick. It has been verified that the 50 μm backward and forward steps (induced by the copper electrodes) did not alter the transition process taking place on the suction side of the wing. The air-exposed electrode was connected to a voltage amplifier (Trek, model 30/20A, gain 3000 V/V), the grounded one was imposed a zero potential. The input signal had a sinusoidal waveform with orders of magnitude for the amplitude and frequency respectively of 10 kV and 1 kHz. The electric power consumed by a plasma actuator was computed from current and voltage measurements following the relation: $P = \frac{1}{T} \int_0^T V(t) \cdot i(t) \, dt$. A high frequency current transformer (Magnelab, model CT-D0.5, sensibility 0.5 V/A, bandwidth 48 Hz-200 MHz) measured the instantaneous discharge current of the actuator $i(t)$, while $V(t)$ is the instantaneous input voltage given by the monitoring sensor of the amplifier. The average on a sufficiently large number of periods $T$ of $V(t) \cdot i(t)$, computed by a digital oscilloscope (Lecroy wavesurfer 454 bandwidth 500 MHz) gives the mean consumed power $P$. This value was then divided by the spanwise length of the electrodes to give the consumed power per unit of electrode length $P_a = P/L$ in W/m. In order to study the influence of ionic wind location on the boundary layer transition, two actuator locations have been successively

![Fig. 1. Characteristics of the ONERA-D wing model. (a) Side view of the DBD actuators on the ONERA-D wing model. (b) Pressure distribution for $\text{AoA} = 1.5^\circ$.](image-url)
tested: 13 and 33% of chord. Measurements in the boundary layer have been carried out using hot-wire anemometry (Dantec Streamline, 90C10 CTA module, 55P15 probes) for different configurations with and without control.

2.2. Natural boundary layer characterization

The pressure distribution along the studied wing model has been measured (Fig. 1 b) and shows a strong suction peak near the leading edge followed by a large zone of deceleration which destabilizes the longitudinal Tollmien-Schlichting (T-S) waves of the boundary layer.

The transition location has been experimentally determined by measuring the RMS signal of a hot wire probe along the wing model at a constant height $y = 1$ mm from the wall (see Fig. 2). The transition location is determined by tracing the tangents of the RMS signal curve (dotted lines in Fig. 2) for the laminar and the growing phases. The abscissa of these two lines intersection gives the transition location. The natural transition occurs at 56% of chord for $U_\infty = 21$ m/s and at 51% of chord for $U_\infty = 24$ m/s.

The measured pressure coefficients have been introduced in the ONERA in-house boundary layer code (3C3D) to compute the mean velocity profiles along the suction side. A stability analysis has been performed on the resulting velocity profiles with the help of an ONERA in-house stability code (Castet). The resulting evolution of the N-factors along the chord is presented Fig. 3 for both studied velocities. Two groups of instabilities are noticeable: the first one is constituted of high frequencies which are damped into the highly decelerated zone of the suction peak, the second one of lower frequencies which are amplified during the large zone of quiet deceleration. The measured transition locations correspond to a N-factor of about 7 for $U_\infty = 21$ m/s and 7.5 for an upstream velocity

![Graph](image_url)
Fig. 4. Evolution of a hot wire RMS signal along the ONERA-D chord for different configurations with and without actuation for a fixed input signal frequency $f = 2$ kHz. $x_{DBD} = 33\%$ of chord: (a) $U_\infty = 21$ m/s (b) $U_\infty = 24$ m/s.

$U_\infty = 24$ m/s. The corresponding turbulence level is approximately $Tu = 0.15\%$ according to the Mack relation ($N_t = -8.43 - 2.4 \cdot \ln(Tu)$ where $N_t$ is the transition N-factor). The frequency of the T-S waves which trigger the transition determined by numerical stability computation is around 1000 Hz for 21 m/s and 1200 Hz for 24 m/s (Fig. 3). As the actuator induces a pulsed body force at the same frequency as the input signal, frequencies close to these one or to one of their harmonics may excite the related T-S waves and promote the transition. We assume that the chosen frequency of 2 kHz is high enough to induce a quasi-steady body force in order to only study the stabilizing mean body force effect. Thermal effects are negligible for the considered values of input signal frequency and amplitude: the maximum temperature increase at the dielectric surface does not exceed 20 °C according to Tirumala et al. Moreover, this temperature increase is found on a small extent (less than 20 mm) near the high voltage electrode.

2.3. Effects of DBD actuation on the boundary layer

In most cases of this study, the frequency of the signal which powers the actuator $f$ is set to 2 kHz and its amplitude $V$ between 13 and 21 kV, allowing to cover consumed powers $Pa$ from 31 to 76 W/m. Probing along the chord at a constant height $y = 1$ mm from the wall have been performed in order to locate the transition for configurations with and without actuation. Mean velocity profiles have been measured 10% of chord behind each actuator position $x_{DBD}$ (measurement at 43% for an actuator at 33% of chord, for example) so that the hot wire probe is far enough from the plasma volume.

Fig. 4 and 5 show the evolution of the hot wire RMS signal for several configurations without and with actuation at $x_{DBD} = 33\%$ of chord. For the cases presented in Fig. 4 and 5 a, the actuation results in a transition delay. Besides, the transition shift is greater when the consumed power $Pa$ increases (Fig. 4), leading to a maximum transition delay of 6% of chord for $U_\infty = 21$ m/s and $Pa = 76$ W/m. Fig. 5 a shows that the transition delay is the same for a given consumed power $Pa$, meaning that the mean body force is the same whatever the values of the electrical parameters $V$ and $f$. However for $U_\infty = 24$ m/s (Fig. 5 b), the transition is delayed for an input signal frequency $f = 2$ kHz.
and an amplitude $V = 19.5$ V but promoted in the case of an actuation at 1200 Hz and 20.4 kV, despite an identical consumed power. The linear stability presented on Fig. 3 b has shown that, at 33% of chord, the instabilities at 2 kHz are damped, whereas those at 1.2 kHz are amplified. In the second case, the pulsed body force, which has the same frequency as the input signal, amplifies the instabilities at 1.2 kHz and leads to a promotion of the transition (unsteady effect). In the first case, the chosen input signal frequency corresponds to damped perturbations and does not induce a destabilizing unsteady effect, so that only the mean body force plays a role on the transition shifting.

For $\chi_{DBD} = 13\%$ of chord (Fig. 6), the transition is promoted for every actuation configurations. The linear stability analysis (Fig. 3 a) shows that at 13% of chord, for all the chosen input signal frequencies, perturbations are amplified. In these cases, the actuation excites the growing perturbations, leading to a promotion of transition. These results are in accordance with the ones of Joussot et al.\textsuperscript{4} who observed that a DBD actuator could delay, promote or let unchanged the transition position depending on its position along a flat plate.

Fig. 7 shows the mean velocity profiles measured for different configurations with and without actuation. The mean velocity $U$ is nondimensionalized by the external velocity of the non manipulated boundary layer $U_e$ and represented as a function of the height from the wall. For $\chi_{DBD} = 13\%$ and 33% of chord, a velocity overshoot appears at $y \approx 1.5$ mm from the wall, also observed by Séraudie et al.\textsuperscript{2} for lower velocities. In the case of a transition delay ($\chi_{DBD} = 33\%$ of chord), the velocity added by the ionic wind increases with the consumed power: there is a positive correlation between the added velocity and the transition delay. For $\chi_{DBD} = 13\%$ of chord, the velocity overshoot is also more important when $P_a$ increases. The maximal velocity overshoot is observed for the largest consumed power as expected.
2.4. Stability computations on experimental data

In order to quantify the stabilization effect, a local stability study has been performed on the experimental mean velocity profiles with and without actuation. It is based on the resolution of the Orr-Sommerfeld system (1):

\[
\begin{align*}
\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} &= 0 \quad (1a) \\
\frac{\partial u'}{\partial t} + U \frac{\partial u'}{\partial x} + \frac{dU}{dy} v' - \frac{1}{Re} \frac{\partial^2 u'}{\partial x^2} &= 0 \quad (1b) \\
\frac{\partial v'}{\partial t} + U \frac{\partial v'}{\partial x} + \frac{\partial p'}{\partial y} - \frac{1}{Re} \frac{\partial^2 v'}{\partial x^2} &= 0 \quad (1c)
\end{align*}
\]

where \( u' \) and \( v' \) represent the velocity fluctuations, \( p' \) the pressure fluctuation and \( U \) the mean velocity profile. \( Re = \frac{U \delta}{\nu} \) is the Reynolds number based on the boundary layer thickness \( \delta \). Using the Orr-Sommerfeld system instead of the Orr-Sommerfeld equation allows to use only the first derivative of the mean velocity profile instead of its second derivative. When the mean velocity profiles derive from experimental measurement, their first derivative is easier to compute with a satisfying accuracy and robustness. The classical modal form of disturbances used in linear stability for the bidimensional case (equation (2)) is then introduced in the system (1) for the resolution.

\[
q'(x, y, t) = \hat{q}(y) \cdot \exp(-\alpha r x) \cdot \exp(i(\alpha r x - \omega t)) \quad (2)
\]

where \( q' \) is a fluctuation, \( \hat{q} \) its amplitude function, \( \alpha r + i \alpha r \) is the complex wavenumber in the longitudinal direction, \( -\alpha r \) corresponding to its spatial amplification rate. The temporal wavenumber \( \omega \) is real in this case where only spatial stability is considered.

Fig. 8 shows the amplification rate of the T-S waves \( \alpha r \) depending on the frequency for each velocity profile. The horizontal dotted line separates the stable and unstable domains. A frequency is amplified when its amplification rate \( \alpha r \) is negative. In the case of the actuator located at 13% of chord (Fig. 8), the actuator locally stabilizes the mean velocity profile when powered at \( Pa = 60 \text{ W/m} \) but greatly destabilizes it when powered at \( Pa = 76 \text{ W/m} \). The stabilization of the mean velocity profile behind the actuator at \( x_{DBD} = 33\% \) of chord (Fig. 8) is clearly seen when the DBD is powered at 76 W/m. When powered at 60 W/m, the actuator stabilizing effect is less perceptible at this station.

More mean velocity profiles are required to evaluate the contribution of DBD plasma actuators in terms of stability into the boundary layer. This study allows to observe locally the mean body force effect which stabilizes the flow by adding momentum to the boundary layer and changing the shape of the mean velocity profile. The differences observed between the plasma actuation effects at different location and for the same electrical power may be due to a competition between the stabilizing mean body force effect and the destabilizing unsteady effects. When the input signal frequency is close to an amplified perturbation, then the transition is promoted even if the mean body force locally shows a more stable velocity profile. This is what happens for the actuation cases at \( x_{DBD} = 13\% \) of chord.

![Fig. 8. Amplification rate of T-S waves as a function of frequency at the location of the velocity profiles from Fig. 7. Profiles location: (a) 23% of chord, \( x_{DBD} = 13\% \) of chord, (b) 43% of chord, \( x_{DBD} = 33\% \) of chord.](image-url)
3. Numerical study

3.1. Modeling of the plasma induced body force

An analytic model has been developed and introduced in an ONERA boundary layer code and is inspired by the work of Kriegseis et al. This work consisted in measuring the velocity field created by a DBD plasma actuator on a flat plate and estimating the body force field components. As the normal component of the body force field is one order of magnitude less intense than the tangential component, only the second one is taken into account in the developed model. Even if the dielectric barrier of the actuator studied by Kriegseis et al. is thinner than the ones used in this study, the general shape of the body force field is supposed to be the same.

The model inputs are the consumed power $P_a$ and the location $x_{DBD}$ of the actuator. The border and intensity of the body force field only depend on $P_a$. The length $D_x$ and height $D_y$ of the body force domain are described by equations 3.

$$D_x = 0.014(1 - 1.2 \times e^{-\frac{P_a}{23}}) \quad (3a)$$
$$D_y = 0.00172(1 - e^{-\frac{P_a}{23}}) \quad (3b)$$

The body force field tangential component is modeled inside the domain by a product of two polynomials in order to respect the general shape of the body force field computed by Kriegseis et al. Their coefficients are then adjusted so that the modeled mean velocity profiles fit as best as possible the experimental ones in the studied case of an actuator located at 33% of chord. Fig. 9 shows the body force field computed by Kriegseis et al. and the modeled...
one for the same power $P_a$ after it has been fitted to the obtained experimental results. Some differences between the two body force fields are noticeable. As the electrode used for this study are wider than those used by Kriegseis et al., the plasma, and as a consequence the body force extent is also wider in the studied case. For a same consumed power, the total force (body force integrated over the bidimensional domain) is approximately the same (16 mN/m for Kriegseis et al.,$^{12}$ and 19 mN/m for the developed model).

### 3.2. Comparison between numerical study and experimental results

In order to evaluate the mean body force effect predicted with our analytic model, a linear stability analysis has been made on the mean velocity profiles computed by 3C3D. Fig. 10 shows the linear stability of the computed actuated boundary layer for the actuator configuration $x_{DBD} = 33\%$ of chord and $P_a = 76$ W/m. The vertical dotted line represents the natural transition position and the solid line the delayed one. The body force effect is visible as a local damping (from 33% to 43% of chord) of all the frequencies, as previously seen by Sraudie et al.$^2$, which leads to a transition delay. The predicted transition delay in this case is 10% of chord, which is slightly overestimated in regard to the experimental one (6% of chord). To enquire about this overestimated delay, the mean velocity profiles resulting from the experimental campaign and computed with the help of the developed model corresponding to this case are compared Fig. 11 b. The mean velocity profile is correctly represented near the wall, meaning that the velocity gradient at the wall is well represented by the model. However, the velocity overshoot cannot be reproduced by the numerical model. This observation can be made for the other actuation configurations (Figs. 11 a and 12). As the mean velocities computed by 3C3D cannot exceed the external velocity $U_e$ at a given station, the boundary

![Fig. 11. Mean velocity profiles with actuation at x/c=43% for $x_{DBD} = 33\%$ of chord. (a) $P_a = 60$ W/m (b) $P_a = 76$ W/m](image)

![Fig. 12. Mean velocity profiles with actuation at x/c=23% for $x_{DBD} = 13\%$ of chord. (a) $P_a = 60$ W/m (b) $P_a = 76$ W/m](image)
layer thickness is defined as the first time this value is encountered and the computation is stopped for the concerned station. Thus, discrepancies around velocity overshoots are likely to happen when using a boundary layer code.

In order to evaluate the role of the velocity overshoot, stability computations have been conducted on the mean velocity profiles from Figs. 11 and 12. For this purpose, the same approach as in section 2.4 has been used. The results of the computations are shown in Figs. 13 and 14. As for Fig. 8, the amplification rate of T-S waves is plotted as a function of their frequency for different locations and consumed powers and gives a local overview of the mean velocity profiles. For $x_{DBD} = 33\%$ of chord (Fig. 13), the stability is slightly overestimated by the analytic model. In the case $Pa = 60$ W/m, the experimental profile is slightly more unstable than the computed one, and the most unstable frequency is lower in the case of the numerical velocity profile. For $Pa = 76$ W/m (Fig. 13b), only a frequency shift between the two stability curves is noticeable. In this case, where the mean body force effect is predominant on the unsteady effect, a slightly overestimated transition delay may be due to the absence of a velocity overshoot.

For $x_{DBD} = 13\%$ of chord (Fig. 14), the computed profiles are more stable than the measured ones especially in the case of $Pa = 76$ W/m (Fig. 14b). This mean velocity profile is the least well represented by the model: the velocity overshoot is the highest and the slope of the velocity profile at the wall is the least well represented, so the difference between the computed mean velocity profile and the measured one is the biggest. For $Pa = 60$ W/m, the differences between the computed and the measured velocity profiles is less pronounced. As a result, the evolution of the T-S amplification rate with the frequency is closer for these profiles than for those in the case $Pa = 76$ W/m. However, the most unstable frequency is lower for the numerical velocity profile than for the experimental one.
The mean velocity profiles from boundary layer computation are generally more stable than the measured ones. As the case $x_{\text{DBD}} = 33\%$ of chord has been used to calibrate the numerical model, having less differences between measured and computed profiles than for $x_{\text{DBD}} = 13\%$ of chord was expected. In any case, modeling the velocity overshoot is necessary to accurately represent the stability of an actuated boundary layer. As a consequence, the use of a boundary layer code is not sufficient to take into account all the effects of DBD actuation on profile shapes and stability in this case. Using a RANS code for future computations will allow to compute the velocity overshoot.

4. Conclusion

In this article, an experimental and numerical work on the effects of DBD plasma actuators on the boundary layer around an ONERA-D airfoil have been presented. A focus has been made on the body force field mean effect, the excitation of the T-S waves by the pulsed body force being avoided. Several locations of the actuator have been tested independently. Experimental observations of the velocity fluctuations show that, for a same electrical power, the actuator may promote or delay the transition depending on its location. These different behaviours may be due to a competition between a stabilizing mean body force and a destabilizing unsteady effect. A maximum transition delay of 6% of chord has been observed. Stability computations were performed on the experimental mean velocity profiles and show that an actuator may stabilize the boundary layer at a specific station but overall promote the transition. So, to conclude on the contribution of DBD actuator on the boundary layer stability, mean velocity profiles need to be measured at several different stations for each case of actuation.

A model which only takes into account the tangential component of the body force field has been developed and implemented into a boundary layer code. The mean velocity profiles with actuation are correctly modeled near the wall but the velocity overshoot near the boundary layer edge cannot be represented. Local stability computations show that the computed mean velocity profiles are generally more stable than the experimental ones. As a consequence, modeling the velocity overshoot is necessary and that is why, the use of a boundary layer code is not sufficient to take into account all the effects on profile shapes and their corresponding stability in this case. Future computations will be performed using a RANS code to avoid this limitation. Besides, for future modeling, the hypothesis of the body force field intensity and borders only depending on the electrical power consumed by the actuator has to be verified.

References