BOUNDARY LAYER TRANSITION CONTROL WITH STEADY AND UNSTEADY DBD PLASMA ACTUATION

M. Forte[1], A. Seraudie[1], O. Vermeersch[1], A. Kurz[2], S. Grundmann[2], C. Tropea[2], J. Pons[3] and A. Leroy[3]

[1] *ONERA, Aerodynamics & Energetics Modelling Department, 2 av. Edouard Belin,, 31055, Toulouse, France*
[2] *Technische Universität Darmstadt, Centre of Smart Interfaces, Flughafenstr. 19, 64347, Griesheim, Germany*
[3] *University of Orléans, PRISME Laboratory,8 Rue Léonard de Vinci, 45072, Orléans Cedex 2, France*

Abstract

This paper presents experimental and numerical investigations dealing with 2D boundary layer transition control on an ONERA-D airfoil using Dielectric Barrier Discharges actuators. The ability of this kind of plasma actuators to delay transition has been assessed using either steady or unsteady mode of actuation. On the one hand, wind tunnel investigations as well as linear stability analysis are conducted in order to study the effect of a steady operated DBD actuator on boundary layer stabilization. The results show a maximum transition delay of about 35% of chord for low freestream velocity ($U_\infty = 7$ m/s). On the other hand, an experiment has been performed using the unsteady force produced by the DBD actuator to achieve Active Wave Cancellation in direct frequency mode. With the help of a closed loop control system, a significant transition delay has been achieved by damping artificially introduced TS waves for free-stream velocities up to $U_\infty = 20$ m/s. This work has been conducted in the framework of the PlasmAero project funded by the European Commission.

1 Introduction

The main objective of this project is to study different kinds of plasma actuators and to assess their ability to control airflows in order to reduce environmental impact of air transport. One possible way to reduce aircraft fuel consumption is to delay boundary layer transition on wing profiles in order to reduce skin friction drag. Basically, the studies dealing with 2D boundary-layer transition delay can be sorted into two categories: on the one hand, steady actuation is used to modify the mean velocity profile in order to make the boundary layer more stable. Different kinds of actuation have demonstrated good results using this approach, like for instance steady suction. On the other hand, unsteady actuation is used to act (or counteract) directly on the instabilities growing within the boundary layer, the wellknown Tollmien-Schlichting (TS) waves, which lead to turbulence for low disturbance level airflow. This approach is called Active Wave Cancellation (AWC). The present study has focused on one specific kind of plasma actuator: Dielectric Barrier Discharge (DBD). This kind of actuator has been widely characterized in quiescent air for different ambient conditions. Moreover, many investigations have shown their ability to control airflows around different kind of bodies: flat plates, cylinders, airfoils. Most of these studies are reported in a recent review [1]. The goal here is to demonstrate the ability of DBD actuator to delay transition by means of either steady or unsteady actuation, as this actuator is able to induce either continuous or unsteady momentum addition to the boundary layer.

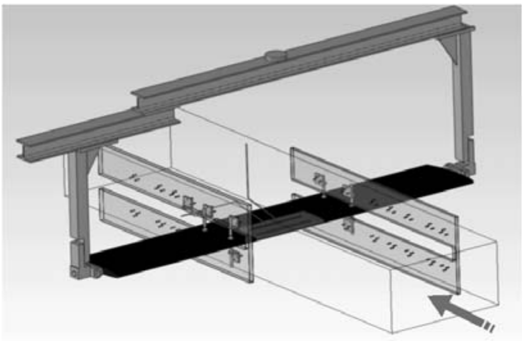

Figure 1: Two-dimensional model of the ONERA-D airfoil mounted inside the wind tunnel

2 Experimental setup

The present experiment has been conducted in the subsonic open-return "Juju" wind tunnel located at the research facilities of ONERA Toulouse. It features a low turbulence level $0.5x10^{-3} < Tu < 0.5x10^{-2}$ depending on the free-stream velocity, which ranges from 5 to 75 m/s. This facility operates at ambient conditions and is well suited for transition experiments. As illustrated in Figure 1, a two-dimensional model based on an ONERA-D profile, having a chord length of c = 0.35 m, is mounted horizontally in the test-section of the wind tunnel.

This profile is symmetric and has been specifically designed for transition control investigations. The angle of attack can be adjusted between α = -8° and α = +3° in order to modify the upper side pressure gradient and thus the natural transition location. Additionally, the model is equipped with 15 pressure taps on the upper side.

Two different kinds of DBD actuator have been used during this experiment:

1) The first one, represented in Figure 2a), consists of a thick dielectric layer: a 5 mm-thick insert (the blue part in Figures 1 and 2) made of dielectric material Lab850 placed at the leading edge region and matching the model shape. This actuator insert allows the model to be outfitted with the desired number of DBD actuators, adhering electrodes asymmetrically on both sides of the Lab850 material which is used directly as the dielectric barrier. For example, Figure 2a) shows

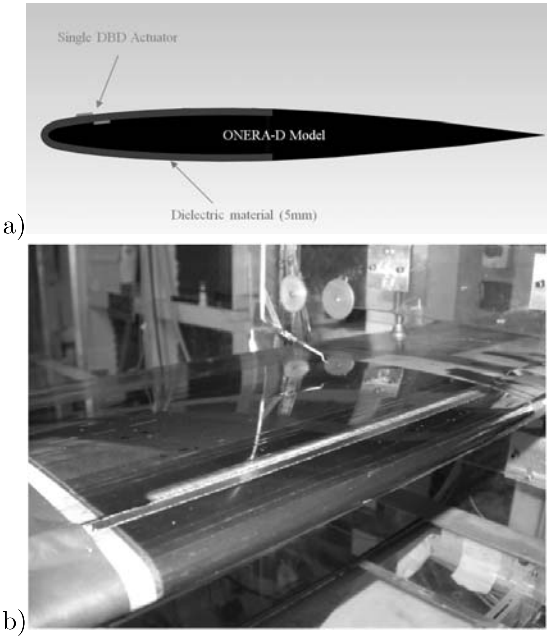

Figure 2: The two kinds of DBD actuator used in this study: a) a thick-dielectric actuator and b) the thindielectric actuator

one single DBD actuator located at x/c = 10% (the downstream edge of the air-exposed electrode is taken as the location reference).

2) The second kind of actuator consists of a much thinner dielectric layer made of Kapton material (≈ 0.2 mm-thick) which is flexible enough to outfit the model as shown in Figure 2b). Whatever the kind of actuator used, electrodes are 30 cm-long in spanwise direction and made of copper tape. Air-exposed electrodes are connected to a TREK power amplifier (model 30/20, ±30kV, 20mA peak) and supplied with AC high voltage while other electrodes are grounded. Moreover, those air-exposed electrodes have been polished in order to reduce their thickness down to 0.05 mm to prevent them from promoting transition. Hot wire anemometry (Dantec Streamline, 90C10 CTA modules, 55P15 probes) has been employed for boundary-layer explorations.

3 Transition delay using steady DBD actuation

The study presented in this section is related to 2D boundary-layer stabilization using the plasma actuator in a continuous mode of operation. Using this approach, a quasi-steady momentum is added to the flow, directly acting on the mean velocity profile of the boundary layer in such a way that the amplification of the disturbances is impeded and transition can be delayed.

3.1 Wind tunnel investigations

In a first step, boundary-layer transition delay is investigated experimentally using one single DBD actuator located at x/c = 10% and operated continuously. The angle of attack of the model is set to $\alpha = 2.5°$ and the experiment has been performed for two different free-stream velocities U_∞ = 7 & 12 m/s, using both thick and thin dielectric actuators for the lowest velocity but only the thick actuator for the highest velocity. The thin actuator is supplied with AC high voltage having an amplitude of V_{DBD} = 7 kV while the thickest actuator is supplied with successively three different amplitudes V_{DBD} = 8.5; 12 and 17 kV. For both actuators, the operating frequency is set to f_{DBD} = 2 kHz. The maximum velocity of the ionic wind induced by the thickest actuator in quiescent air is about 4.5 m/s at the highest voltage amplitude. Figures 3 and 4 present typical results for U_∞ = 7 & 12 m/s respectively. Velocity fluctuations are computed from boundary-layer explorations along the chord, moving the hot-wire probe at a constant distance from the wall, with and without control. The location of the transition is deducted from the fluctuation increase. The natural transition is located at x/c ≈ 40% for U_∞ = 7 m/s and at x/c = 26% for U_∞ = 12 m/s. In all cases, the ignition of the plasma actuator leads to a transition delay. As expected, the transition is shifted progressively downstream when the amplitude of the voltage is increased since the mechanical effect of the actuator (ionic wind) increases. Maximum transition delay recorded during this experiment are 35% of chord for U_∞ = 7 m/s and 20% of chord for U_∞ = 12 m/s. The efficiency of the thin actuator could be largely improved by increasing the operating frequency of the supplied signal, which was not possible with our power amplifier.

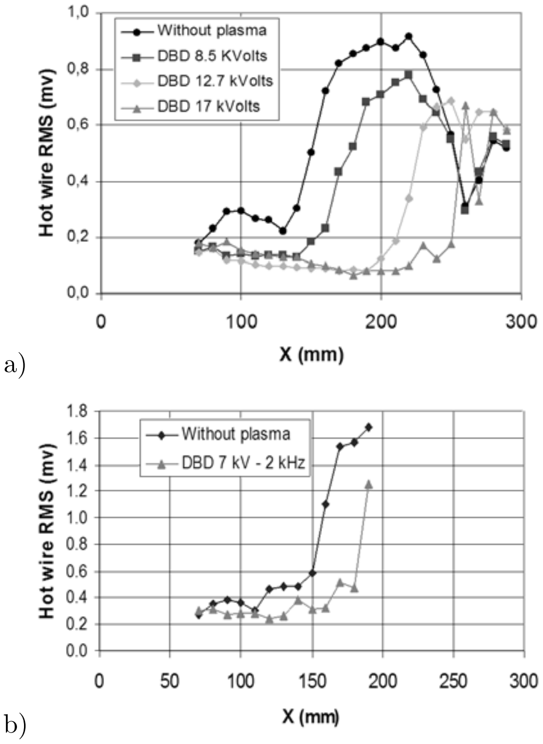

Figure 3: Transition delay with steady DBD actuation for U_∞ = 7 m/s : a) with the thick-dielectric actuator and b) with the thin-dielectric actuator

3.2 Numerical investigations

In order to confirm that this transition delay is due to the modification of the mean velocity profile, the control of the boundary layer with steady actuation has been investigated from a numerical point of view. At first, boundary-layer computations have been performed for the baseline cases (without plasma) using an ONERA code (3C3D). Then, an artificial ionic wind profile (with a simple model well described in [2]) has been numerically added at the location of the actuator

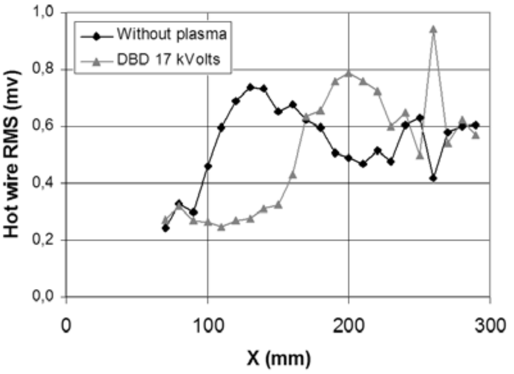

Figure 4: Transition delay with steady DBD actuation for $U_\infty = 12$ m/s with the thick-dielectric actuator

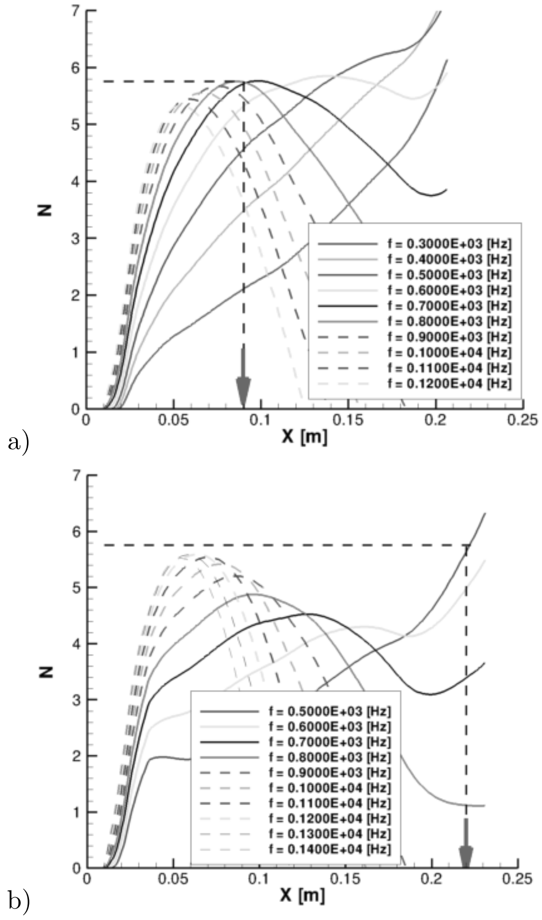

Figure 5: Evolution of the N-factor along the chord of the model ($U_\infty = 12$ m/s, $\alpha = 2.5°$) without control (a) and with control (b)

(x/c=10%) to the mean velocity profiles coming from these base flow computations in such a way that the resulting profiles fit the experimental ones. Finally, exact stability computations have been conducted on these modified profiles using the envelope strategy so as to compute the amplification N-factor with an ONERA code (Castet). Typical results of the linear stability analysis are given in Figure 5 which presents the evolutions of N-factor along the chord of the model for several instability frequencies in the baseline case (a) and for the controlled case (b).

The aerodynamic configuration is the same than for the case presented in Figure 4 with $U_\infty = 12$m/s. As the natural transition location is known from the experiment (x_t/c $\sim$ 26% or $x_t = 0.09$ m), we can deduce the corresponding transition N-factor $N_t = 5.8$. Then, using this value in the controlled case plot, we can observe that transition location is shifted downstream ($x_t = 0.22$ m), not far from what has been observed experimentally ($x_t = 0.16$ m). In conclusion, stability computations as well as experiments show that DBD plasma actuator used in a steady mode has a stabilizing effect on the boundary layer. The modification of the mean velocity profiles is such that the amplification of the disturbances is impeded and transition can be delayed.

4 Transition delay using unsteady DBD actuation

One other possible way to delay 2D transition is to use unsteadily operated actuators to act (or counteract) directly on the Tollmien-Schlichting waves growing inside the boundary layer and triggering transition. This approach is called Active Wave Cancellation: the goal is to generate an artificial perturbation with an unsteady force production so as to damp natural TS waves by destructive interference. Transition is delayed because TS wave amplitude has been reduced locally. Grundmann and Tropea [3] have conducted experiments using this approach on a flat plate. They used a single high-frequency driven DBD actuator with square wave modulation to generate artificially introduced waves. Another possible solution is to make use of the DBD plasma actuator unsteady force production during one cycle of the operating frequency and to directly operate the cancellation actuator at the TS wave frequency. In fact, several recent studies [4] have shown that DBD actuator produces a local unsteady force mainly due to the different discharge regimes between the positive and the negative half cycles. This asymmetric behavior enables to use DBD actuator in direct frequency mode. A careful adjustment of the phase relation between the TS waves and the actuator excitation signal can thereby potentially cancel the waves. Thus, the use of a closedloop system, which detects the waves and optimizes the actuation, will be necessary.

The experimental set-up used for this study is quite the same than the one presented in the previous section except that the angle of attack is set to $\alpha = 2°$ and that the model is outfitted with two DBD actuators, as illustrated in Figure 6. The upstream actuator DBD1 (x/c = 10%) serves as disturbance source to artificially excite a single frequency TS wave train while DBD2 (x/c = 30%) is utilized as the transition control device. The experiments have been split into two phases. During an initial testing phase, the feasibility of the direct frequency mode for active wave cancellation had to be verified. In order to do so, a set-up employing a beat frequency approach without the use of a closed-loop controller was chosen, re-

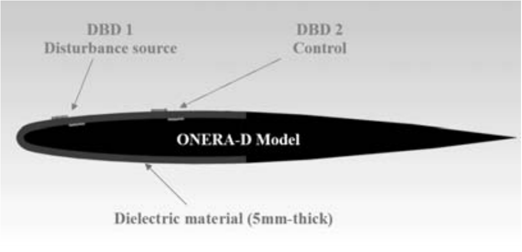

Figure 6: Experimental set-up for the Active Wave Cancellation study

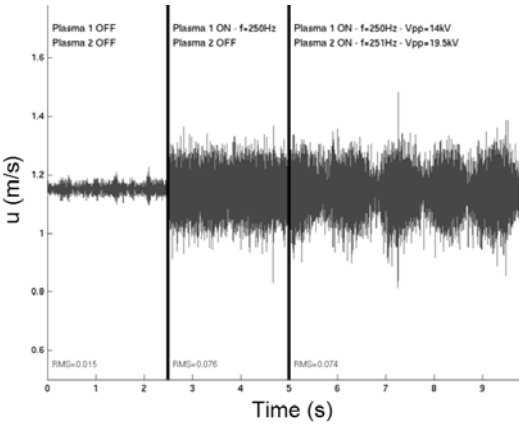

Figure 7: Time trace of u velocity component given by hot-wire probe located inside the boundary layer at x/c = 40% for the base flow (left), with excitation (center) and with excitation and control (right)

producing the experiments of Grundmann and Tropea. This allows for time efficient parameter studies to find appropriate settings and the corresponding attenuation rates. In the second testing phase, transition delay on the wing model has been demonstrated with closed-loop control applied.

4.1 AWC without closed-loop control

For this set of measurements the excitation frequency at the upstream actuator DBD1 has been set to a value close to the naturally occurring TS frequencies (f_{DBD1} = 250 Hz). As the artificially excited waves travel downstream, they reach the control actuator (DBD2) which was operated at a slightly shifted frequency (f_{DBD2} = 251 Hz) in order to create a beat frequency with the two signals due to the continuously changing phase relation. Some typical results from these experiments are presented in Figure 7 for a free-stream velocity of U_∞ = 7 m/s.

The hot wire measurements shown were taken at x/c = 40% inside the boundary layer at a wall-normal distance of y = 0.4 mm. The base flow case (left part of the plot) exhibits a low fluctuation level within the hotwire signal of 0.015m/s. With excitation (middle part of the plot) this disturbance level is raised to 0.076m/s. Applying the control (right part of the plot) a slow oscillation of the amplitude of the TS waves farther downstream the second actuator develops, with a maximum amplitude above the one of the unaffected waves (amplification) and minimum amplitude below the unaffected wave (damping) resulting in an almost unchanged RMS-value of 0,074m/s in this case. Figure 8 shows a time trace of the excited TS wave signal with smaller time scale (dashed line) in comparison to the base flow case (solid line), revealing that a clean TS wave train has been produced by DBD1. Two important results emerge from these experiments. First of all the unsteady momentum production of the plasma actuator can be utilized to excite TS waves, if applied at the appropriate position, amplitude and a frequency the flow is susceptible to. Secondly and most important, the direct frequency approach for flow control proved to be applicable and can be utilized for Active Wave Cancellation.

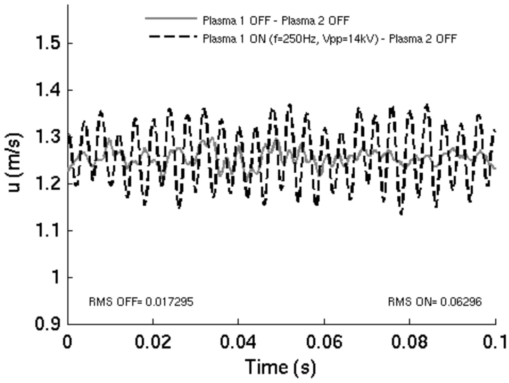

Figure 8: Time trace of u velocity component given by hot-wire probe located inside the boundary layer at x/c = 40% for the base flow (solid line) and with DBD1 turned on (dashed line)

4.2 AWC with closed-loop control

In order to have a permanent optimized phase shift between TS waves generated by DBD1 and the controlling unsteady force induced by DBD2, a robust extremum-seeking control algorithm has been used. This algorithm, which has previously been successfully applied for flow control purposes, was supplied by the TU Berlin.

The system utilizes the signal of a stationary hot wire probe (x/c = 40%, y = 0.2 mm) as an error sensor to automatically optimize the control function. This control algorithm runs on a dSPACE real-time processing unit. Due to its robustness this algorithm is well suited to control artificially excited, single-frequency TS waves. By slowly and periodically deflecting the system out of its current operating point (perturbation), the gradient f' of the error signal according to a change of the controlled variable, which in this case is the phase shift, is determined. The phase relation between TS wave train and the flow structures created by the plasma actuator is then continuously adapted along this gradient, which drives the system into a minimum.

Following the promising beat frequency experiments, closed-loop control has been applied in order to demonstrate transition delay using the direct frequency approach. The free-stream velocity and the angle of attack remain at U_∞ = 7 m/s and α=2° respectively. A spectral analysis of the stationary hotwire signal reveals the frequency content of the flow, as shown in Figure 9. Plotted is the power spectral density in dB/Hz over frequency at a wall-normal position of y=0.2mm. In the base flow case (DBD1 off, DBD2 off) two frequency peaks, one at 250 Hz and a wider peak around 340 Hz, are prominent. These frequencies represent the naturally occurring TS waves present in the boundary layer for the given flow situation. However, as it has been shown with linear stability analysis, well described in [5], frequencies around 340Hz are damped downstream of DBD2, with the limit for the unstable frequency band being about 300Hz. A

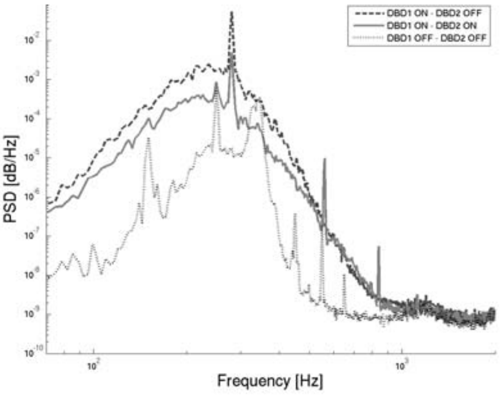

Figure 9: Spectral analysis of the error sensor signal (x/c = 40%, U_∞ = 7 m/s) for the base flow (DBD1 off, DBD2 off), with excitation (DBD1 on, DBD2 off) and with closed-loop control (DBD1 on, DBD2 on)

frequency sweep in the unstable range revealed that an excitation at 280 Hz leads to the cleanest TS wave signal at the location of the error sensor. Consequently it was decided to use this frequency for the subsequent AWC experiments. Figure 9 shows that introducing the excitation at 10% chord (DBD1 on, DBD2 off) produces the expected peak around 280Hz as well as an overall increase in the turbulence level as transition is being promoted. This increase is visible at the error sensor, since its location is close to the point of transition for the excited case (∼ 47% chord). Applying the control (DBD1 on, DBD2 on) the TS peak at 280Hz can be reduced by about one order of magnitude. This effect is accompanied by a decreased the overall turbulence level. Figure 10 depicts a typical result of the transition delay studies. Plotted is the RMS-value of the longitudinal velocity fluctuations recorded at various downstream locations at a constant distance above the wall within the boundary layer. The dark blue curve (◊) represents the natural transition case with the onset of transition at about 60% chord, i.e. neither the disturbance source nor the control actuator is operating. Turning on the disturbance source, the TS wave amplitude is significantly increased at f = 280 Hz which moves the transition region upstream to about 40% chord (□). Then, with the control system active, the region of transition can be shifted downstream significantly by about 10% chord length (○). Even though the unsteadiness of the force production of DBD plasma actuators is exploited in this work to conduct active wave cancellation it may not be neglected that a net force is produced, which modifies the mean flow, i.e. the boundary-layer velocity profile. This modification can by itself lead to a stabilization of the boundary layer as presented in section 3, hence delay transition. Complementary measurements have been carried out in order to exclude a possible boundary-layer stabilization due to continuous addition of momentum. To quantify this effect, the momentum generation of DBD2 has been measured in quiescent air using Pitottube measurements. The maximum achievable velocity, 10 mm downstream of the active electrode, was determined to be ∼ 0.6 m/s at the prescribed plasma frequency of 280Hz using this electrode configuration, dielectric material and thickness. In order to deactivate the active wave cancellation and to quantify the effect of a pure momentum addition of this magnitude, the recorded average wall-jet velocity has been reproduced at a plasma frequency of 1 kHz using DBD2. This frequency is located well outside the unstable frequency range and is assumed not to have any destabilizing effect on the boundary layer. The transition delay due to continuous momentum addition is small compared to the effect of the active wave cancellation and is in the order of 1-2% of chord length. For higher Reynolds numbers it can be assumed that this effect will be reduced even further. This experiment proves that the achieved results can clearly be attributed to the unsteady force production of the DBD plasma actuator and are not the result of a modified mean flow.

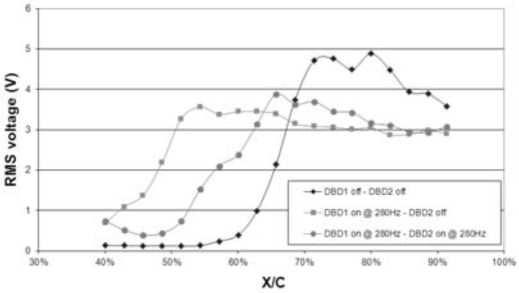

Figure 10: RMS value of hot-wire signal along the chord of the airfoil for the base flow, with excitation and with closed-loop control (U_∞ = 7 m/s)

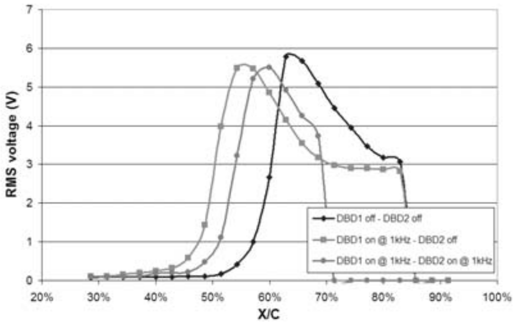

Figure 11: RMS value of hot-wire signal along the chord of the airfoil for the base flow, with excitation and with closed-loop control (U_∞ = 20 m/s)

The same experiment has been conducted with higher free-stream velocity U_∞ = 20 m/s. The angle of attack has been slightly reduced to $\alpha = 1.5°$ in order to have the natural transition location near x/c = 60% as for the previous case. This time the frequency of the disturbance source is set to f_{DBD1} = 1 kHz which is close to the frequency of the most unstable perturbations for this aerodynamic configuration. The evolutions of velocity fluctuations along the chord, shown in Figure 11, prove that transition delay has been achieved (4% of chord) using DBD plasma actuator with a closed-loop control system. Detailed results about this last experiment will be given in a forthcoming paper.

5 Conclusion

In this paper, the ability of DBD actuator to delay 2D boundary-layer transition has been assessed by means of either steady or unsteady actuation. On one hand, wind tunnel investigations as well as linear stability analysis have shown that DBD actuator used in a steady mode has a stabilizing effect on the boundary layer. The modification of the mean velocity profiles is such that the amplification of the disturbances is impeded and transition can be delayed. A maximum transition delay of about 35% of chord has been achieved for low freestream velocity (U_∞ = 7 m/s). On the other hand, an experiment has been performed using the unsteady force produced by the DBD actuator to achieve Active Wave Cancellation in direct frequency mode. With the help of a closed loop control system, a significant transition delay has been achieved by damping artificial TS waves for free-stream velocities up to $U_\infty = 20$ m/s.

Acknowledgments

The present work has been performed within the framework of the PlasmAero project funded by the European Commission (Grant agreement nr. 234201). The authors would like to thank the members of this project for sharing their knowledge and the fruitful discussions. The authors would like to thank also N. Goldin and R. King from the Technische Universität Berlin for sharing their control algorithm [5] crucial for the AWC experiment as well as their help and advice.

References

[1] N. Bénard and E. Moreau, 2012, *EHD Force and Electric Wind Produced by Plasma Actuators Used for Airflow Control*, Proc. of the 6th AIAA Flow Control Conference, AIAA Paper 2012-3136, 2012.

[2] A. Seraudie, O. Vermeersch and D. Arnal, *DBD plasma actuator effect on a 2D model laminar boundary layer. Transition delay under ionic wind effect*, Proc. of the 29th AIAA Applied Aerodynamics Conf., AIAA Paper 2011-3515, 2011.

[3] S. Grundmann, and C. Tropea, *Active cancellation of artificially introduced Tollmien-Schlichting waves using plasma actuators*, Experiments in Fluids, Vol. 44, No. 5, pp. 795-806, 2008.

[4] M. Forte, J. Jolibois, J. Pons, E. Moreau, G. Touchard and M. Cazalens, *Optimization of a dielectric barrier discharge actuator by stationary and non-stationary measurements of the induced flow velocity: application to airflow control*, Experiments in Fluids, Vol. 43, pp. 917-928, 2007.

[5] A. Kurz, C. Tropea, S. Grundmann, M. Forte, O. Vermeersch, A. Seraudie, D. Arnal, N. Goldin and R. King, *Transition delay using DBD plasma actuators in direct frequency mode*, Proc. of the 6th AIAA Flow Control Conference, AIAA Paper 2012- 2945, 2012.