



PROJECT FINAL REPORT

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1. Final publishable summary report

1.1 Executive summary

The overall objective of the project was to study the principles of flow control aimed at improving the aerodynamic performance of the wings of transport aircraft and thereby reducing their fuel consumption. The study of these flow control principles has been segmented into three WPs.

The aim of WP1 was to control the buffet on a two-dimensional supercritical wing profile operating in **turbulent regime**. Only the process using a tangential jet flow control was effective in T-112 TsAGI wind tunnel tests. The DBD actuator check was ineffective for the tested configuration. The other plasma actuators by spark discharge have shown some ability to reduce the amplitude of the buffet phenomenon, but not to suppress it.

The other two WPs, WP2 and WP3, concerned wing profiles operating in **laminar regime**. The objective of WP2 was to characterize and control the laminar buffet on a two-dimensional profile. Tests carried out in the ONERA S3Ch transonic wind tunnel have successfully characterized the occurrence of laminar buffet in the Mach-Incidence envelope. A numerical simulation of the LES type has well reproduced the dynamics of laminar buffet. Active control by blowing upstream of the shock was very convincing to delay the occurrence of the buffet. The passive control by bump 3D has shown an attenuation of the phenomenon without completely removing it.

The objective of WP3 was the study of two flow control principles using DBD actuators to delay the laminar-turbulent transition generated by the presence of transverse flow on a swept profile. The first principle consists in the creation of a counter-current stopping the transverse flow. The second consists in the formation of successive micro-jets normal to the wall creating a series of virtual roughnesses (VR) whose spacing corresponds to a wavelength "killer" of that present in the transverse flow.

A key issue of all present designs was the unwanted but significant promotion of unsteady boundary-layer instabilities. The spatial distribution of the induced forcing achieved by the actuators designed for transition control by crossflow velocity reduction may have been too inhomogeneous.

About the VR-type actuators, numerical studies indicated that an order of magnitude stronger forcing would have been needed.

This low TRL project permitted the development of several new flow control technologies then tested on sub-scale wing configurations in wind tunnels. Numerical simulations have contributed both to the design of flow control technologies and to the re-building and analysis of results.

Incontestable scientific advances have been made on the control of turbulent buffet and on the characterization and control of laminar buffet on two-dimensional profiles, and on the control of transverse flow. Several realizations of flow control technologies using DBD and plasma actuators have been evaluated in laboratories and wind tunnels.

The main recommendation is to continue research efforts, both experimentally and numerically, on buffet control techniques, particularly in laminar regime, on swept wing configurations.

1.2 Summary description of project context and objectives

BUTERFLI is the acronym for "BUffet and Transition delay control investigated within European-Russian cooperation for improved FLIght performance". It is a small focused collaborative project funded under the European Transport Item of the FP7 Cooperation Work Program. Involving 5 Russian partners and 7 European partners, BUTERFLI has addressed the coordinated call Aeronautics and Air Transport (FP7-AAT-2013-RTD-RUSSIA) and more specifically the field of "Theoretical and experimental study of flow control for improved aircraft performance". BUTERFLI has developed new scientific knowledge and tools that will be used in the mid-long term by the industry to improve the performance (drag, lift, weight) of aircraft wings, thus contributing to reduce the environmental footprint of air transport. Thus, the BUTERFLI project will contribute to progress towards the objectives of the Report of the High Level Group on Aviation Research called "Flightpath 2050: Europe's Vision for Aviation", which formulates an ambitious goal : "In 2050 technologies available allow a 75% reduction in CO₂ emissions per passenger kilometer" (relative to the capabilities of typical new aircraft in 2000).

In the frame of this global strategy, three complementary objectives were pursued in the frame of BUTERFLI:

- alleviating the buffet phenomenon on transonic supercritical turbulent wings by two different control means (tangential jet blowing and plasma discharge);
- understanding and alleviating the buffet phenomenon in the shock region on transonic laminar wings by several control means (bump, perforation blowing);
- delaying laminar turbulent transition by controlling crossflow instability waves with plasma discharge, using both linear and nonlinear control principles.

WP1 objectives: Alleviating the buffet phenomenon on transonic supercritical turbulent wings:

Current aircraft airfoils are designed with optimized geometry to give the best aerodynamic performances in a chosen part of the flight envelope. The further improvements of cruise characteristics of aircraft without flow control are limited. With the continued objective of increasing aircraft performances whilst reducing the environmental impact, investigations have been carried out to find innovative solutions to control flow conditions by the use of small size actuators. WP1 has investigated experimentally and numerically flow control strategies using tangential jet blowing and plasma actuators in order to improve the aerodynamic performance of the supercritical wing on transonic regimes including buffet regimes. The main objectives of WP1 are the following:

- to understand physics and develop plasma actuators for buffet control on transonic supercritical turbulent wing;
- to develop tangential jet blowing system for buffet control on transonic supercritical turbulent wing;

- to develop strategies for alleviating the buffet phenomenon on transonic supercritical turbulent wings by several control means (tangential jet blowing and plasma discharges);
- to increase the buffet margin in the flight envelope;
- to improve the aerodynamic performance of the wing during cruise regime;
- to give recommendations for application of buffet control devices (tangential jet blowing and plasma discharges) on aircraft.

WP2 objectives: Buffet on transonic laminar wings:

The second work package (WP2) of the Buterfli project was dedicated to the investigation and control of the buffet phenomenon on laminar wings. The objectives were the following:

- Characterize the 2D flow past the laminar wing as a function of Mach number and incidence,
- Characterize the Buffet phenomenon in laminar conditions,
- Develop control concepts to alleviate the Buffet phenomenon ,
- Validate experimentally the control strategies,
- Build an experimental database for CFD simulations and physical understanding,
- Provide data for the synthesis on the behavior of laminar wing and the control of the Buffet phenomenon,
- Gives recommendation for the application of the physical and control concepts developed in the work program.

It may be necessary to recall here that the shock dynamics on laminar wings had been little described before this Buterfli project. The only work that is known to the author of this document is the one by Dor et al. in 1989 (J.B. Dor, A. Mignosi, A. Seraudie, and B. Benoit. Wind tunnel studies of natural shock wave separation instabilities for transonic airfoil tests. In Symposium Transsonicum III, pages 417-427. Springer, 1989) in which it is described that the flow is not unsteady in the laminar case, unlike the turbulent case where a strong unsteadiness exists. The turbulent case is known as turbulent buffet and has been intensely investigated (see for instance the work of Jacquin et al. released in 2009 - L. Jacquin, P. Molton, S. Deck, B. Maury, and D. Soulevant. Experimental study of shock oscillation over a transonic supercritical profile. AIAA J. 47(9), 2009).

This absence of known unsteadiness of the shock for the laminar wing was the main motivation of the WP2 of the Buterfli project. The first part of the project was hence dedicated to the **characterization of the flow** past a **laminar wing**, and to the search of an unsteady **shock dynamics** similar to the turbulent phenomenon. The second part of the project was dedicated to the **control of the flow**, to reduce shock unsteadiness.

WP3 Delaying laminar turbulent transition by controlling crossflow instability waves

The overall objective of WP3 was delaying laminar turbulent transition in crossflow-dominated swept-wing boundary layers by DBD plasma actuators. The aim was to develop and test devices for controlling the growth of crossflow instability waves either by changing the instability characteristics of the laminar boundary layer or by virtual-roughness (VR) type actuators which act similar to discrete roughness elements (DRE) and delay transition by a nonlinear disturbance interaction mechanism. In detail, the objectives listed in the BUTERFLI WP3 description of work were:

- to develop and qualify DBD plasma actuators suitable for delaying crossflow-dominated laminar-turbulent transition
- to assess the potential and robustness of the concepts of transition delay by crossflow velocity reduction and nonlinear disturbance attenuation, respectively
- to identify the pros and cons of the different actuator designs
- to better understand the physics of laminar flow control by DBD plasma actuators in swept-wing boundary layers
- to further develop and validate the numerical tools for studying laminar flow control in swept-wing boundary layers by DBD plasma actuators
- to provide guidelines and recommendations for further development of these laminar flow control concepts towards an application for transition delay on swept wings of commercial aircraft.

1.3 Description of the main S&T results/foreground

WP1 Alleviating the buffet phenomenon on transonic supercritical turbulent wings

Description of the methodology

The work is organized within the six tasks: 1) Supercritical wing; 2) Plasma actuators; 3) Tangential jet blowing system; 4) Wind tunnel tests; 5) Numerical simulations and re-building; 6) Synthesis and concept assessment.

Several buffet control means are considered:

- Tangential jet blowing (developed by TsAGI);
- Two different implementation of actuator based on dielectric barrier discharge (developed by ITAM and JIHT);
- Plasma actuator based on spark discharge with wedge (developed by ITAM);
- Plasma actuator based on submicrosecond spark discharge (developed by JIHT).

The partners involved in WP1:

TSAGI	Development of tangential jet blowing system, experiments in T-112 TsAGI WT without and with flow control devices
MIPT	Numerical simulations of baseline configurations, configuration with tangential jet blowing and with DBD
ITAM	Development of actuator based on spark discharge with wedge, preliminary testing in ITAM
JIHT	Development of actuator based on submicrosecond spark discharge, preliminary testing in JIHT
DLR	Numerical simulations of baseline configurations and configuration with DBD
ONERA	Numerical simulations of baseline configurations and configuration with DBD
SUKHOI	Comparison of numerical and experimental results, analysis and concept assessment
AIRBUS	Recommendations for application of buffet control devices on aircraft

The work is divided into numerical and experimental parts. Experimental part consists of the following experiments:

- Preliminary testing of DBD and submicrosecond spark discharge in JIHT;
- Preliminary testing of DBD and “wedge plasma actuator” in ITAM;
- WT tests of baseline configuration with P-184-15SR airfoil in TsAGI T-112 WT;
- WT tests of configuration with tangential jet blowing in TsAGI T-112 WT;
- WT tests of configuration with different plasma actuators in TsAGI T-112 WT.

The RANS or URANS approach with the turbulence model of Spalart-Allmaras have been used by MIPT, DLR and ONERA for numerical simulations of baseline configurations as well as configuration with DBD. MIPT also has performed calculations for the configuration with tangential jet blowing.

Description of the WP results

The experiments were carried out in the transonic wind tunnel T-112 TsAGI. WT T-112 (Fig. 1) has square test section $0.6 \times 0.6 \text{ m}^2$; perforated top and bottom walls; stagnation temperature

– environmental temperature; stagnation pressure – atmospheric; Reynolds number based on free-stream parameters and chord length (200 mm) – $\sim 2.6 \times 10^6$; standard run duration – 300 s.



Figure 1. T-112 TsAGI transonic wind tunnel with installed wing model and pylons for compressed air supply.

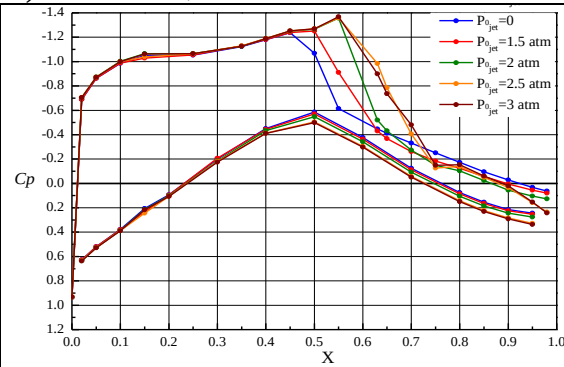


Figure 2. Pressure coefficient C_p for different regimes; $M=0.75$, $AoA=6^\circ$

A model of the airfoil P-184-15SR is performed in the form of rectangular wing with the same cross section (Fig. 1) which is located between the side walls of the test section. The side walls in the region of the model installation have optical windows, which enable optical measurements. The model contains the equipment for tangential jet blowing and various measurements performed during WT tests. The following measurements were carried out and the equipment listed was used: Schlieren-type visualization of flow over the upper surface; pressure taps; Kulite sensors for unsteady pressure measurements on the upper surface; wake investigations using the rake to measure pressure profile; pressure taps on wind tunnel walls. The model was equipped with a slot for tangential jet blowing. The slot was located at 60% of chord and had height of 0.15 mm.

Test conditions were the following: $M=0.61\div 0.81$ is range of Mach numbers; $\alpha=0\div 6^\circ$ is range of angle of attack (AoA); boundary layer transition was fixed; range of total pressure of the blown jet is $P_{0jet}=1.5\div 3$ atm.

The main purpose of the present work is to determine how the tangential jet blowing affects the flow. The jet should suppress shock-induced separation and delay buffet onset to higher AoA and to higher C_L values.

Pressure coefficient C_p on the model surface corresponding to the different jet intensities is shown in Figure 2. One can see that the increase of a jet stagnation pressure moves the shock wave downstream and leads to a better C_{pTE} recovery.

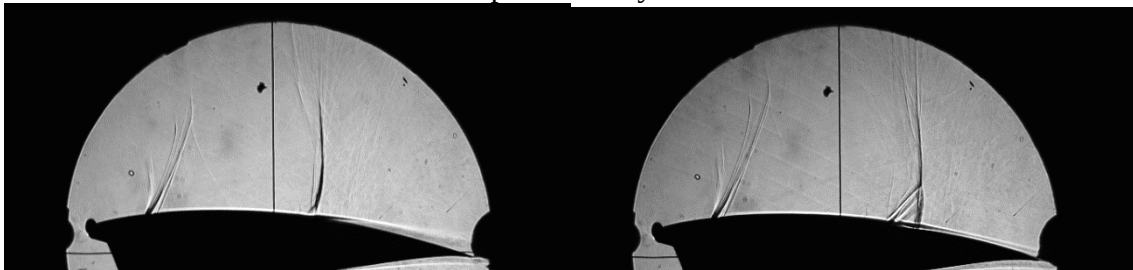


Figure 3. Schlieren images for baseline configuration (left) and configuration with tangential jet blowing (right) at $P_{0jet}=3$ atm; $\alpha=5^\circ$, $M=0.76$

In figure 3, one can see the difference between shock wave locations for the case without blowing (left column) and for the case with jet blowing (right column). It is clearly seen from

the right column that there is no separation under the shock and at the trailing edge for the cases with jet blowing.

One of the main parameters to be obtained in this experiment was buffet frequency. The pressure difference in time was obtained using Kulite sensors for each regime and the spectra were calculated. Figure 4 shows spectra for the case of $\alpha=6^\circ$ at section $x/c=0.75$ and for different Mach numbers without jet blowing (left) and with jet (right). It is clearly seen that there is a discrete peak at ~ 140 Hz on baseline configuration. In the case of jet blowing, the discrete peak ~ 140 Hz disappears while the level of pulsations in this region increases.

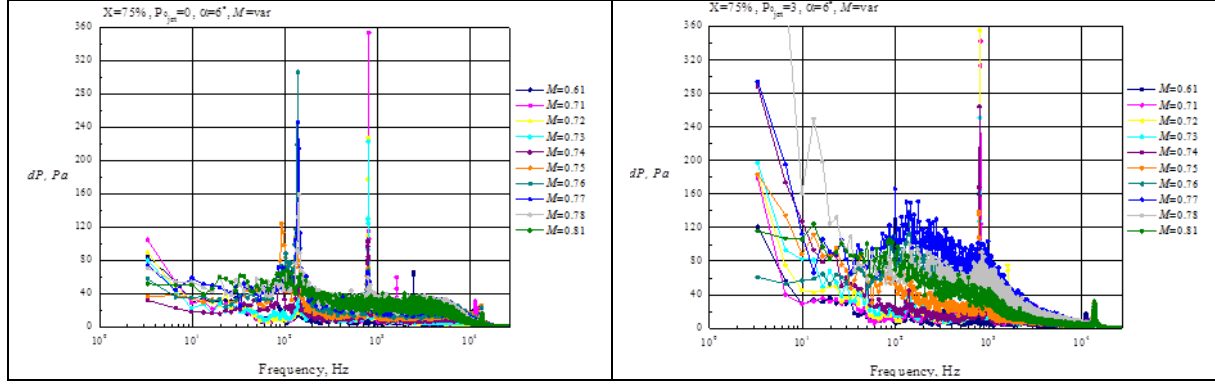


Figure 4. Spectra of pressure pulsations for $\alpha=6^\circ$ for baseline (left) configuration and tangential jet blowing (right) with $P_{0jet}=3$ atm, $x/c=0.75$

The RANS or URANS approach with the turbulence model of Spalart-Almaras is used. The Mach number and AoA corrections are required for relatively good agreement of 2D free-stream numerical simulations (without taking into account wind tunnel walls) with experimental results. The results showed good agreement with experiments taking into account this correction (Figure 5).

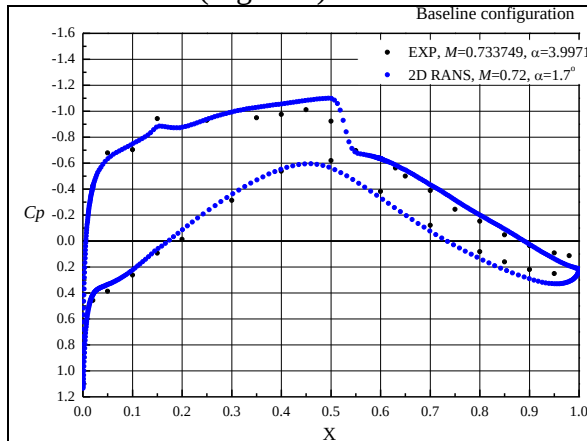


Figure 5. Pressure coefficient distribution on the airfoil; comparison of experimental (black) and numerical (blue) results with corrected free-stream values.

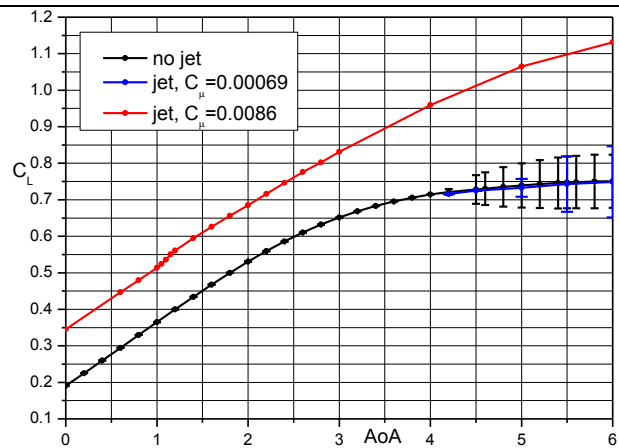


Figure 6. Lift curve for $M=0.73$ with and without tangential jet blowing; black curve – without jet, blue – weak jet $C_\mu=0.00069$, red – strong jet $C_\mu=0.0086$.

2D URANS numerical simulations show that there are oscillations from $\alpha=5^\circ$. Buffet frequency varies from 99 Hz for $M=0.72$ to 118 Hz for $M=0.74$. 3D URANS simulations for the 3D model taking into account wind tunnel walls give buffet frequency ~ 157 Hz while experimental value is about 138-140 Hz.

Lift curves calculated with 2D URANS approach with free-stream boundaries for different jet intensities are shown in Fig. 6 ($M=0.73$). Black curve corresponds to the case without jet

blowing, while blue curve corresponds to the case with weak jet blowing ($C_{\square}=0.00069$). Vertical bars on the curves designate RMS values of oscillations obtained in URANS. It should be noted that the deviation of lift curve from the linear regime is near $\alpha=2-2.5^{\circ}$ while buffet onset regimes begin from $\alpha=4.2^{\circ}$ (bars on black curve).

Bars on blue curve begin to grow from $\alpha=4.5^{\circ}-5^{\circ}$. This trend shows that even weak tangential jet blowing delays buffet onset. Red curve corresponds to the case of relatively strong jet blowing with $C_{\square}=0.0086$. There are no oscillations of C_L in this case and there is no buffet. One can conclude that tangential jet blowing delays buffet.

The next flow control concept which was investigated within WP1 is plasma actuators. The first actuator developed by ITAM was constricted DBD (CDBD) (Figure 7a). The actuator consists of grounded encapsulated electrode, open saw-shaped electrode and includes the additional metallic islands placed downstream and not connected with anything. The actuator provides the formation of discrete plasma filaments i.e. the local regions of energy deposition. Position of the actuator was chosen to provide plasma region upstream of the shock. The second actuator used was a so-called sliding discharge (SD) (Figure 7b). The actuator was made in the same manner as classical DBD with additional open electrode placed downstream and connected with the ground. The actuator provides the conditions for extending of plasma region at the distance between exposed electrodes. It was shown in T-325 wind tunnel tests that there is no significant influence of the discharge on mean flow in comparison with the “plasma off” case.

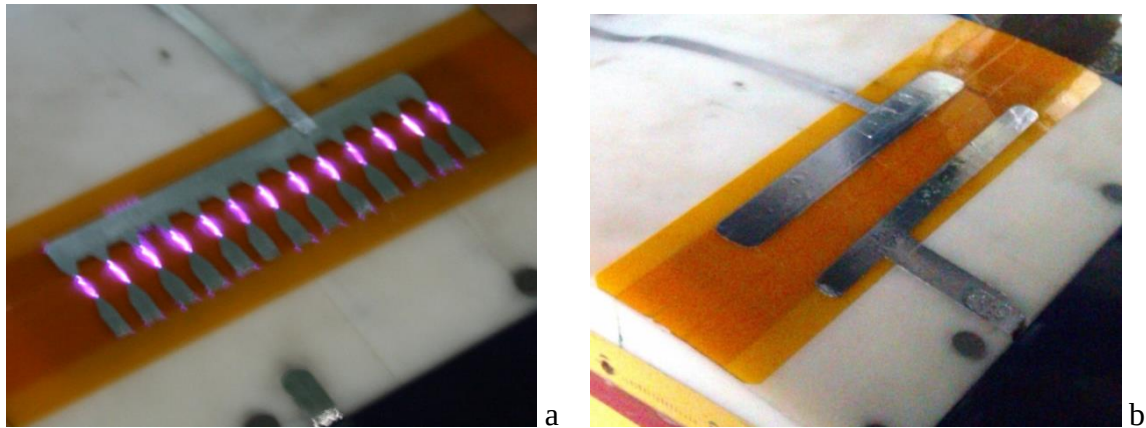


Figure 7. Photos of bump with actuators: a) CDBD, b) SD.

The next series of experiments was carried out in TsAGI T-112 transonic wind tunnel. The experimental model was similar to those presented in Figures 1. The model is made from steel and has a cavity on the upper surface for plasma actuator inserts installation. The flow around the model was studied by schlieren visualization, surface pressure distribution measurements and Pitot measurements in the wake of the wing using wake rake located downstream of the model.

The data demonstrate that there is no any influence of DBD plasma actuator developed by ITAM on mean as well as unsteady flow parameters at transonic regimes.

The image of the insert with DBD actuator developed by JIHT is presented in Fig. 8. The edge of the exposed electrode was at the position $x/c=0.44$. The discharge was powered by sinusoidal voltage with the frequency $\sim 65-70$ kHz and the amplitude 7-13 kV. Actuator was operating either in a continuous mode or in a modulated one with frequencies $F_m=144$ Hz, 1.3 kHz and duty cycle $S=2$. It was obtained that the discharge at the studied parameters creates a wall jet with typical velocities 4-6 m/s (Fig. 8). In general, one can conclude that the effect of the DBD plasma actuator on the buffet phenomena is small.

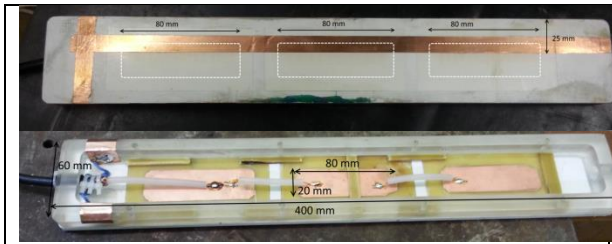


Figure 8. Insert of JIHT with DBD.

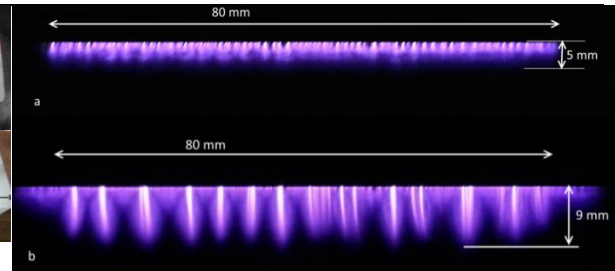


Figure 9. Images of the DBD in a single section of the insert. a) $U_a=7\text{kV}$, quasi-homogeneous, b) $U_a=13\text{kV}$, constricted.

The effect of a DBD actuator on the flow around the TsAGI airfoil P-184-15SR has been studied numerically for steady and unsteady (buffet) transonic regime using 2D RANS/URANS approach. The DBD is simulated using an empirical model of source terms in x-momentum and energy conservation equations developed by TsAGI in WP3. Numerical simulations are in good agreement between partners (MIPT, DLR, ONERA) and confirm that the effect of the DBD plasma actuator on the buffet phenomena is small.

The next plasma actuator developed by ITAM was spark discharge actuator with wedge. Control strategy in this study is based on the increasing of the resistance of the boundary layer to adverse pressure gradient and separation generated by the shock. The insert to wind tunnel model is equipped by “plasma wedge” actuators (Fig. 10) distributed along the span. The discharge frequency and excitation mode were varied during experimental tests.

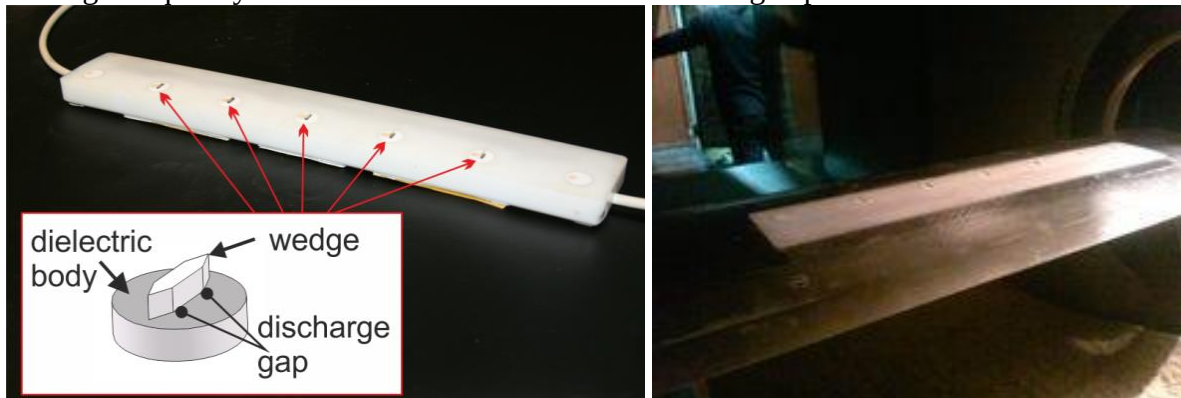


Figure 10. Plasma-wedge actuator insert and the wing with installed actuator.

The spectra of shock wave oscillations were obtained basing on the results of schlieren data processing. Excitation of plasma in continuous mode (Fig. 11) results in stabilization of shock wave oscillations. It can be seen from the figures that amplitudes of the main and other peaks significantly decrease if the plasma actuators are excited (except for the case $f=150\text{ Hz}$ which is close to the buffet frequency). Plasma excitation in modulated mode also lead to decreasing of shock oscillations intensity.

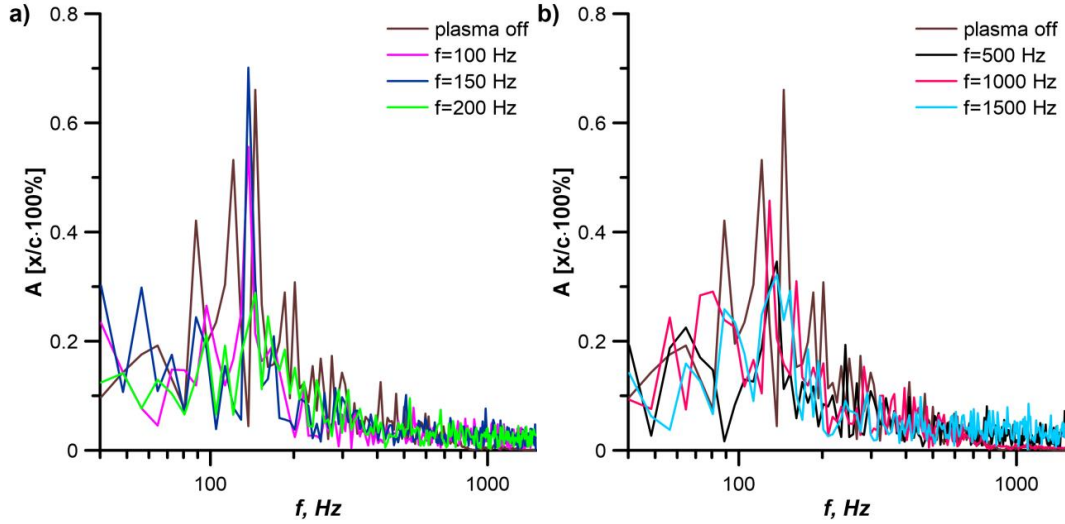


Figure 11. Spectra of shock wave motion at continuous mode of discharge excitation ($M_\infty=0.76$, $\alpha = 5^\circ$).

Microsecond spark discharge generates large-scale vortex structures and fast jets in ambient air. The general idea of performed investigations is that a set of surface spark actuators could be arranged on the airfoil upstream of the region of SWBL interaction for reducing the buffet amplitude or delaying its onset. To implement the discharge section to the airfoil model, the dielectric insert was manufactured. Photos of actuators are shown in Fig. 12.



Figure 12. Two inserts and wing model with spark actuator installed in TsAGI T-112 WT.

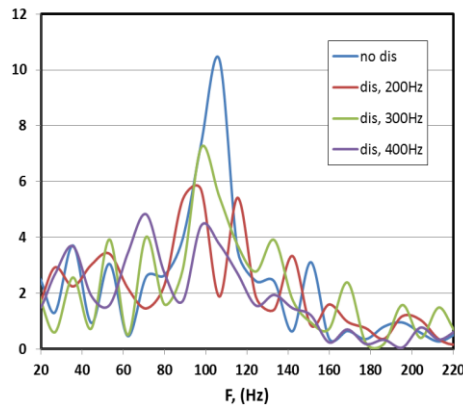


Figure 13. Amplitude spectra for $\alpha=5^\circ$, $M=0.76$.

Different discharge frequencies were tested in a range from 200 to 1180Hz for 1st actuator and in a range from 790 to 1790Hz for 2nd actuator. The spark was located in front of shock or directly below, and the discharge cavity expansion takes place behind the shock. Amplitude spectra corresponding to the presented Schlieren images are shown in Fig. 13, and results obtained can be evaluated as positive because a decrease in the amplitude of oscillations occurs.

In conclusion one can note that there is a moderate effect of decreasing of shock oscillation amplitude for case of buffet.

In general, it can be concluded that new control means for buffet control have been developed; tangential jet blowing and plasma actuators with spark discharge. Tangential jet blowing is more effective than plasma actuators. It increases the buffet margin in the flight envelope and improves the aerodynamic performance of the wing during cruise regime.

Airbus has prepared recommendations for further application of tangential jet blowing on aircraft:

- The use of 2D experiments is valuable to understand the effectiveness of flow control devices allowing a down select of concepts for further study. However future experimental work investigating flow control to delay buffet should have experiments designed to output ΔC_l buffet due to flow control. 3D wing studies should be undertaken.
- Active flow control with blowing is effective at delaying buffet but integration at aircraft level needs to be investigated further regarding mass flow and power requirements.
- Buffet suppression flow control appears to offer some benefits to enable high span wings.

Global conclusions for the WP

Several buffet control means are considered in the WP1:

- Tangential jet blowing (developed by TsAGI);
- Two different implementation of actuator based on dielectric barrier discharge (developed by ITAM and JIHT);
- Plasma actuator based on spark discharge with wedge (developed by ITAM);
- Plasma actuator based on submicrosecond spark discharge (developed by JIHT).

One can conclude the following:

1. For DBD effect, both experimental and numerical results show that DBD has very small and negligible influence on considered transonic flow.
2. The results show that considered actuators with spark discharge are able to slightly influence on the mean flow. These actuators can decrease the amplitude of shock wave pulsations but not to suppress totally.
3. The tangential jet blowing is more effective than plasma actuators. The tangential jet blowing moves the shock wave location downstream. The increase of a jet intensity leads to a more downstream location of the shock and a better recovery of the trailing edge pressure. The jet suppresses the shock-induced separation. It is clearly seen that tangential jet blowing delays buffet onset in lift and angle of attack domain. It increases the buffet margin and improves the aerodynamic performance of the wing during cruise regime.

WP2 Buffet on transonic laminar wings

Description of the methodology

WP2 of the Buterfli project is a cooperation project between 5 partners: ONERA (The French Aerospace Lab), USTUTT (University of Stuttgart), TsAGI (Russian Central Aerodynamics Institute), MIPT (Moscow Institute of Physics and Technology) and Airbus Group Innovations and Sukhoi as industrial partners. The work was organized in 7 tasks, as listed below:

- T2.1 Laminar airfoil design (ONERA),

- T2.2 Bump design (USTUTT),
- T2.3 Blowing jet design (ONERA),
- T2.4 Manufacturing of the airfoil and of the control devices (ONERA),
- T2.5 Laminar wing wind tunnel testing (ONERA),
- T2.6 Numerical simulation and rebuilding (TSAGI, MIPT, ONERA, USTUTT),
- T2.7 Concept assessment and synthesis (SUKHOI, AIRBUS).

Partners responsible for each task are indicated inside the brackets. These responsibilities relate more particularly to the following actions:

- In WP2, ONERA was responsible for the design of the laminar wing, for the wind tunnel tests performed in the transonic S3Ch facility of the ONERA Meudon research center, for the design of the jet device and for the simulation of the baseline configuration without control.
- USTUTT was responsible for the design of the bumps and for the numerical simulations of the baseline, jet and bump configurations.
- TsAGI and MIPT were responsible for the numerical simulations of the baseline, jet and bumps configurations.
- The industrial partners, Airbus Group Innovations and Sukhoi, were responsible for describing the implications of the research findings obtained in WP2 for the future technologies of commercial aircrafts regarding laminar flow and flow control.

All partners were strongly involved in the scientific decisions that governed the progress of the project. This allowed an efficient interplay of the numerical and experimental approaches that were used to details the shock dynamics of the laminar wing and its control.

This ensemble of tasks brought the project from the initial choice of the airfoil design to the final testing of the control devices in the transonic wind tunnel. Numerical and experimental approaches were hence combined. Numerical simulations were used right at the beginning to design the laminar wing. Then wind tunnel experiments were used to establish the physics of the shock dynamics in the laminar setting and to provide the data necessary to design the control devices. In a next step, the control devices were manufactured and tested in the wind tunnel. As will be apparent in the presentation of the main results, a good agreement was found between the numerical prediction of the effect of the control devices and experimental observations.

Description of the WP results

In WP2, an experimental analysis of the transonic flow past a laminar two-dimensional wing (Figure 14) has been undertaken in order to understand the effect of laminar flow upon the dynamics of the shock wave that forms on the upper surface of the wing.

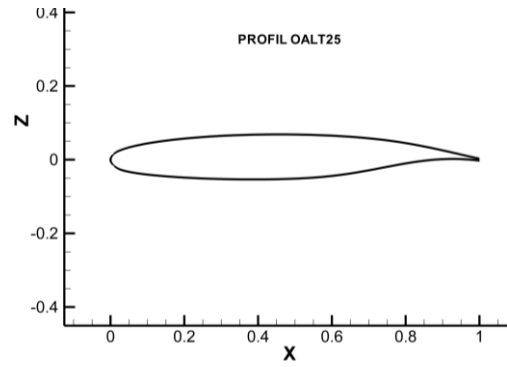


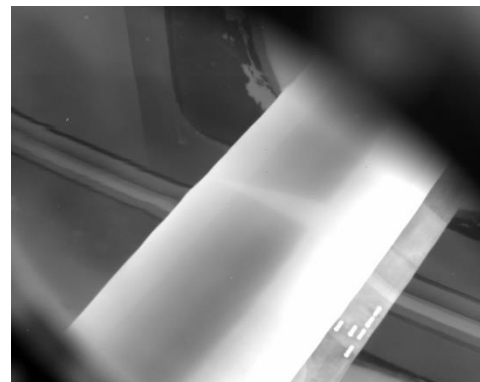
Figure 14. OALT25 airfoil shape in chord units.

Figure 15(a) shows the experimental apparatus installed in the test section of the S3Ch transonic wind tunnel at ONERA, which features a roughly square section of 800mm long sides. Figure 15(b) is a photography obtained with an infrared camera. This infrared image indicates the heat transfer at the upper surface of the wing. It allows in this specific case to identify an increased heating in a cone forming from the leading edge of the wing and induced by a roughness placed there on purpose to validate the capacity of the infrared techniques to detect transition to turbulence. This method was used throughout the study to validate the laminar development of the boundary layer above the wing.

The experimental investigation considered laminar and turbulent configurations, corresponding to free and forced transition respectively. In forced transition cases, the boundary layer tripping device was installed at 7% of chord. Several other chord wise locations were also investigated (25%, 35%, 40%, 52% and 60% of chord).



(a) Test section and wing



(b) Infrared image

Figure 15. Experimental setup in the S3Ch transonic wind tunnel.

The shock wave that forms at the upper surface is shown in Figure 16. The flow is laminar up to the shock wave. The shock foot stands above a laminar separation bubble visible here from the light grey area present right above the airfoil top surface. The existence of this laminar separation bubble has been shown to play a key role in the unsteady dynamics of the shock wave.

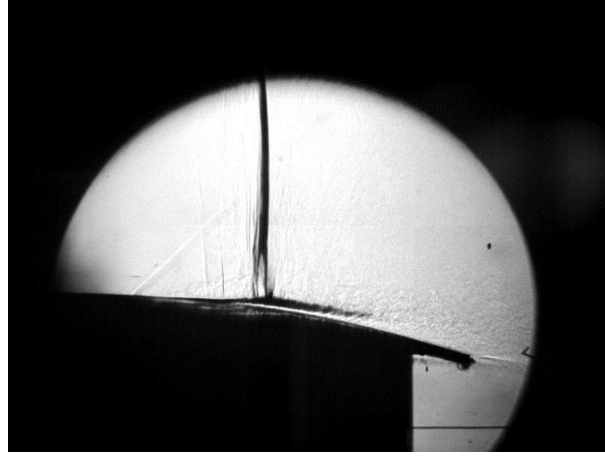
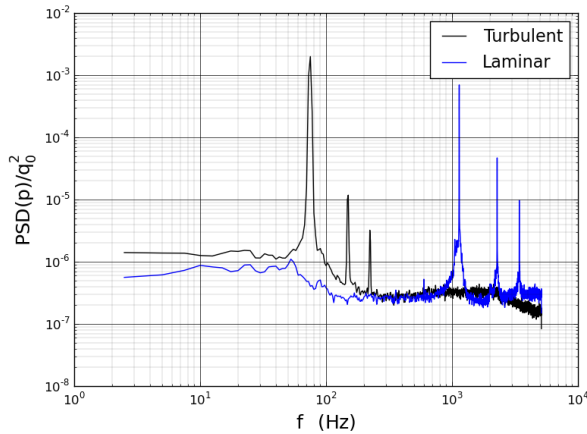
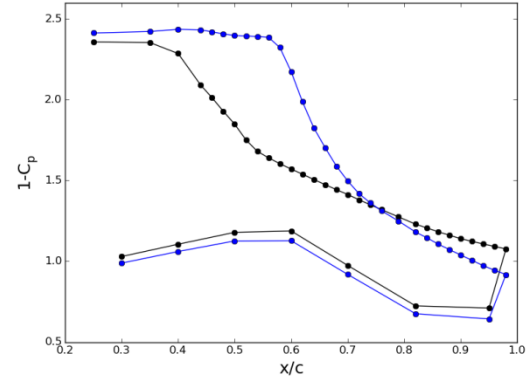


Figure 16. Schlieren view of the flow above the airfoil, with the shock in the middle of the field of view, in the laminar case.

The first important result obtained during the project is the finding of an unsteady dynamics of the shock wave for high enough Mach number and angle of attack, quite similar to the buffet phenomenon known to occur for turbulent conditions. Figure 17(a) shows the pressure spectra of a sensor located in the trailing edge region of the wing, on the upper surface, for the laminar and turbulent cases (the turbulent case serves as a reference). The turbulent case exhibits a well-marked dynamics slightly below 100Hz, which corresponds to previously established results, while the laminar case exhibits unsteadiness, also well-marked, at a frequency an order of magnitude higher, at about 1100Hz. The finding of this unsteadiness represents the first main outcome of the project.



(a) Pressure spectra



(b) Pressure distribution in laminar (blue) and turbulent (black) conditions for $(\text{Mach}, \alpha) = (0.735, 4^\circ)$

Figure 17. Difference between the laminar and turbulent dynamics.

Figure 17(b) shows the difference in pressure distribution along the chord of the wing in the laminar and turbulent cases, and indicates that the shock forms at a more downstream station in the laminar than in the turbulent case. Also remarkable, in the laminar case, is the slight pressure increase ahead of the shock wave, which indicates the presence of the laminar separation bubble mentioned earlier.

The critical conditions for the laminar and turbulent buffet phenomena were tracked by monitoring the Mach numbers and angles of attack for which the peaks illustrated in Figure 17(a) become dominant in the pressure spectra. As shown in Figure 18, critical conditions align on a single line in the map (Mach, AoA). Interestingly the laminar buffet establishes for lighter conditions than turbulent buffet and turbulent buffet occurs only for a limited range of angle of attack. Below 3° angle of attack, no turbulent buffet could be observed, unlike the laminar case. This offset in the threshold of the laminar and turbulent buffet is important as laminar flows are always prone to become prematurely turbulent (as a consequence of wear or dirt deposit on the wing surface for example), and this means that conditions below laminar threshold will not lead to the turbulent unsteadiness, in the case when such turbulent event occurs. This is interesting for application purposes.

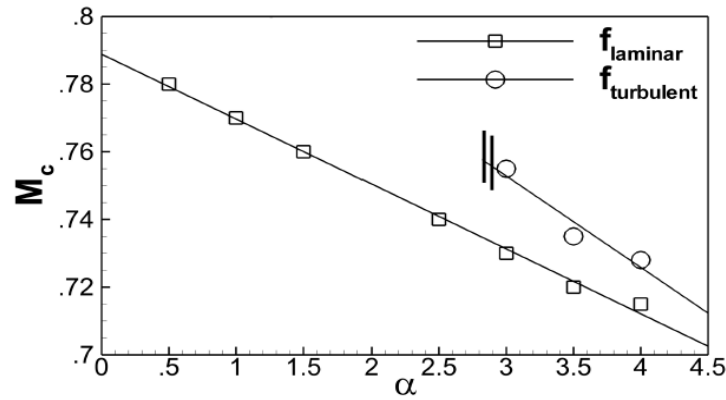
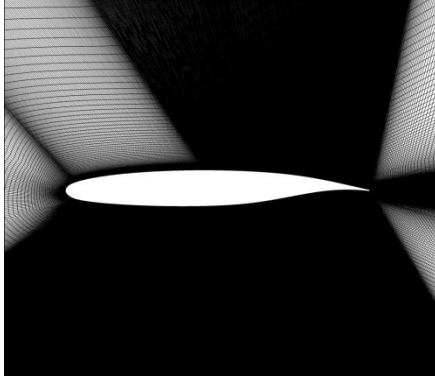


Figure 18. Critical conditions in (Mach,AoA) for the establishment of buffet in laminar and turbulent conditions.

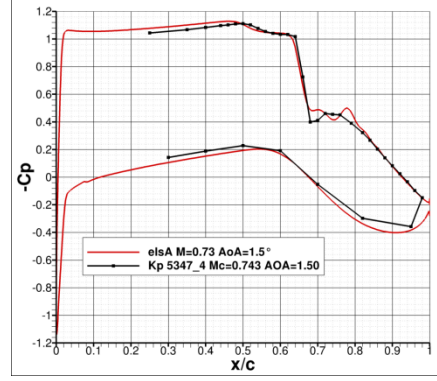
Numerical simulations using RANS and URANS models have been used to confront experimental data. RANS methods were successfully used to simulate the steady flow solution around the airfoil in the laminar and turbulent cases up to buffet conditions. In the turbulent case, RANS methods are able to converge in buffet conditions, i.e. manage to filter out the unsteadiness of the shock wave in order to recover the steady flow solution. In this case, URANS simulations give access to the frequency of the shock oscillations, which compare favourably (a few Hz difference is observed) to experiments.

In the laminar case, buffet conditions could not be handled by RANS simulations and URANS only showed preliminary results (further research is needed on this topic). An illustration of RANS capabilities to capture the flow field around the airfoil in laminar conditions below buffet is given in Figure 19. Figure 19(a) displays one of the meshes that were used to compute the baseline configuration. Figure 19(b) shows the good comparison between the RANS simulation with the transition criterion and the experimental data. In particular, the laminar separation bubble present under the shock foot is well-predicted by the simulation.

The unsteadiness of the laminar buffet has been approached numerically by using an LES model of the flow. Figure 20(a) shows the flow around the airfoil, particularly the turbulent structures present at the lower surface of the wing (due to the forced transition close to the leading edge that is applied there) and those present behind the shock wave and formed in the laminar separation bubble under the shock foot. The comparison between the pressure spectra obtained in the LES simulation and the experiment is shown in Figure 20(b). The LES is capable of capturing the laminar buffet phenomenon, its frequency and its amplitude. The analysis of the flow fields obtained with the LES data will help understanding the buffet phenomenon better in the future.



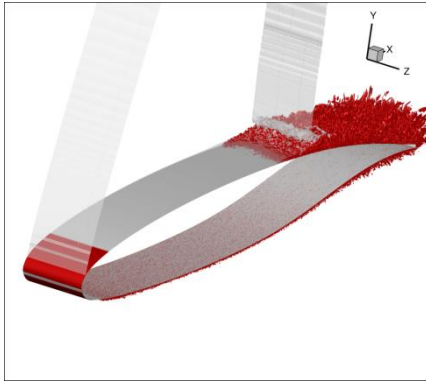
(a) Illustration of the mesh around the laminar airfoil



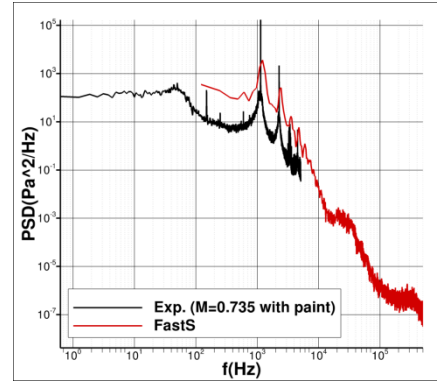
(b) Comparison between RANS simulation results and experiment for $(M_{exp}, AoA)=(0.743, 1.5^\circ)$ in the laminar case

Figure 19. Numerical simulation of the baseline (uncontrolled) configuration.

The unsteadiness of the flow has been controlled using two control strategies, both aiming at controlling flow separation behind the shock wave, which is one of causes of the observed unsteadiness, through the positive effect of longitudinal vortices formed by these devices. The first device is illustrated in Figure 20(a) and consists of a series of jets aligned in the span wise direction and oriented perpendicular to the flow above the wing, with a 30° angle of incidence. Such a configuration promotes the formation of the longitudinal vortices mentioned above. The jet design has been obtained through numerical RANS simulations and optimization over various parameters of the setup, including the jet angles to the main flow and position in chord.



(a) Visualisation of the turbulence developed around the airfoil and obtained by the LES simulation



(b) Comparison of pressure spectra at the trailing edge between the LES simulation and the experiment

Figure 20. Results obtained for the unsteady LES simulation of the flow around the laminar airfoil in the laminar case.

Figure 21(b) shows the second control device, which is a three-dimensional bump, also employed in a series aligned in the span wise direction. Such bumps are traditionally used for wave drag reduction, but are also beneficial for buffet minimization. The bumps have been shape optimized using RANS simulations. The final design consists in a widening geometry of

very small thickness, and allows the formation of longitudinal vortices at the side flanks of the geometry due to the transverse pressure gradient.

The simulations for the design of the two control devices were first calibrated on the experimental data obtained for the baseline, uncontrolled configuration. The control devices were then manufactured and tested in the wind tunnel. The results from the experimental tests of the control devices are shown in Figure 22, in terms of spectra of wall pressure fluctuations at the upper surface of the wing.

In Figure 22(a), the effect of the jets in a situation with laminar buffet is investigated for increasing total mass flow rate. Starting from the baseline configuration with the peak at about 1000Hz identifying the laminar flow unsteadiness, increasing the mass flow rate leads to a decrease of the intensity of this peak and a shift to lower frequencies. With a total mass flow rate of 4g/s and above the peak is completely suppressed, meaning that the flow has been fully stabilized. Interestingly the jets were also successful in controlling the turbulent buffet phenomenon, although the location of the jets is downstream of the mean position of the shock. Thus jets can be used to control both laminar and turbulent situations.

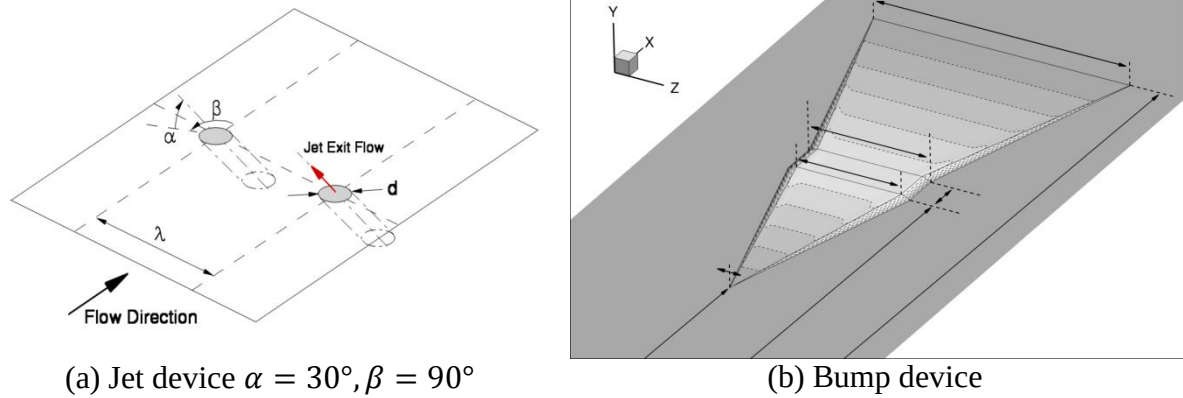
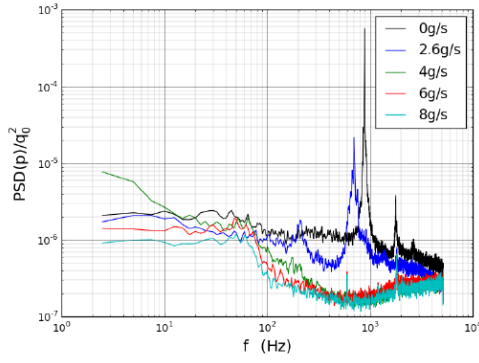
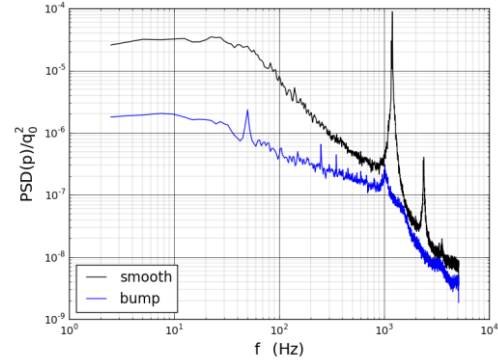


Figure 21. Control devices for the laminar buffet.

In Figure 22(b), the effect of the bump is also described in terms of pressure spectra. The bump is evidenced to decrease the intensity and the frequency of the unsteadiness of the laminar buffet phenomenon. The unsteadiness is strongly attenuated, yet not completely suppressed.



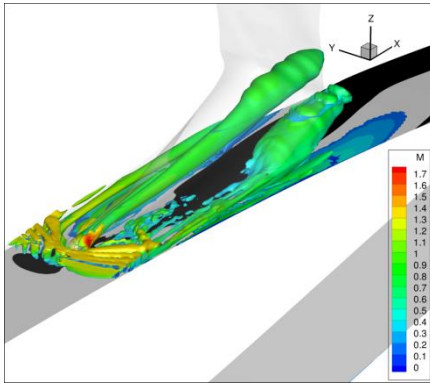
(a) Effect of the blowing jets on the pressure spectra at $(M, AoA) = (0.74, 4^\circ)$ for various values of the jet mass flow rate.



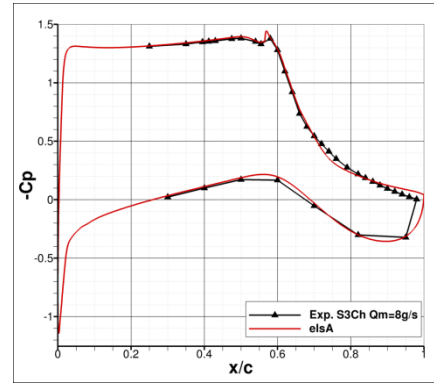
(b) Effect of the bump on the flow unsteadiness at $(Mach, AoA) = (0.73, 3.5^\circ)$. Pressure spectra at 60% of chord.

Figure 22. Experimental validation of the positive effect of the control devices to reduce the shock unsteadiness.

Numerical simulations of buffet control by the fluidic vortex generators (VG) are illustrated in Figure 23. The jets are located at 56% of chord that is about 4% of chord ahead of the mean position of the shock wave in the laminar unsteady case. Such a downstream position allows keeping the laminar boundary layer on the fore part of the wing, hence reducing viscous drag, while having control leverage upon the flow, as illustrated in previous figures. The longitudinal vortices are shown in Figure 23(a) as they form upstream of the shock, go through it and develop downstream, reducing the extent of separated flow in the rear part of the upper surface (in this figure separated flow is shown in black). Figure 23(b) shows the comparison of the jet RANS simulation with experimental data, indicating a good match between the two. This means that RANS simulations are capable of making quantitative prediction of the effect of the control.



(a) Illustration of the vortex formed at the jet exit

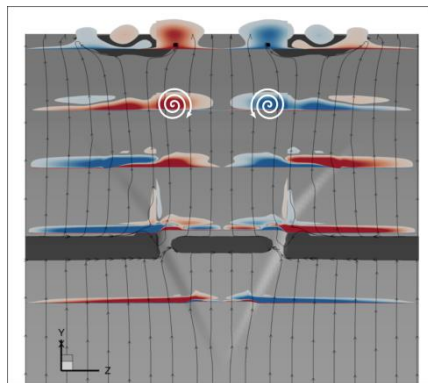


(b) Comparison of the pressure distribution along the airfoil between experiment and simulation.

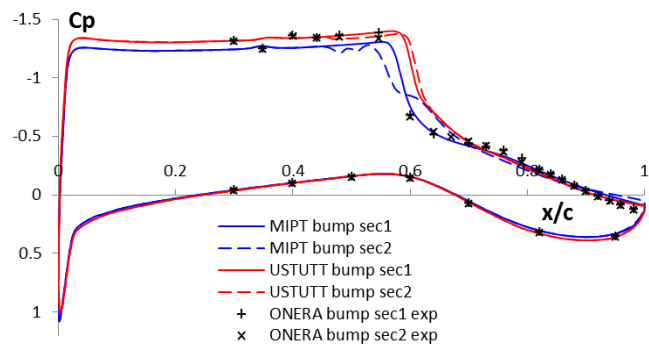
Figure 23. Simulation of the blowing control device.

The flow produced by the bumps (a total of 11 are present along the span of the wing) is shown in Figure 24(a). As explained before, the side flanks of the bump generate longitudinal vortices that develop along the rear part of the wing and help the flow staying attached at the surface. This reduced separation area is the primary enabler of the reduction in buffet unsteadiness illustrated in Figure 24(b). Figure 24(b) shows the comparison between RANS

simulations and experiment for the mean pressure distribution along the wing chord, in the case when transition is forced at 35% of chord (unfortunately no simulation taking into account the transition of the boundary layer could be achieved in the project for the bump configuration). A good match is obtained, showing here also that RANS methods are capable of predicting the flow. The reduction of the unsteadiness by the bumps in the laminar case could however not be simulated during the project but should clearly be a matter of future investigation, in order to confront experimental evidence.



(a) Illustration of the bump effect, with the formation of longitudinal vortices to control flow separation behind the shock wave



(b) Comparison of pressure distribution along the airfoil between several simulations and wind tunnel experiments

Figure 24. Simulation of the bump control device.

The way the results may be used in the future to reduce drag has been analysed by Airbus Group Innovations. In this analysis a simplified method of relating 2D buffet delay to wing buffet onset has been developed. Buffet suppression flow control has been identified to enable laminar flow wings with reduced wetted area. However analysis suggests that although the viscous drag is reduced with the smaller wing the increase in compressibility drag cancels out any overall benefit. Additionally benefits from the reduced area wing needs to be offset against (i) power offtake requirements to drive the flow control, (ii) System mass implications and (iii) the fact that some of the wing planforms may have degraded high lift performance, handling qualities, flutter, or fuel volume which may limit how far the beneficial planform parameters can be exploited.

Given that the active flow control devices require power to function it may be needed to consider if they can be switched on only when needed rather like how spoilers are operated to protect the wing in gusts or manoeuvres. In this case the response time to activate the system will also need to be investigated. Flow control could also be considered as an enabler for increased dash performance of existing planforms. It is an open question if the airlines would be prepared to pay for this ability.

Global conclusions for the WP

The goals that were assigned to WP2 of the BUTERFLI project have all been achieved. Most importantly

- An unsteadiness shock dynamics has been uncovered in the laminar case,
- The shock dynamics exhibits a typical frequency an order of magnitude larger than the turbulent phenomenon,

- The physics of the unsteadiness in the laminar and turbulent cases appears different,
- Control devices have been designed through numerical simulations calibrated upon the wind tunnel test results of the baseline configuration,
- Experimental wind tunnel tests confirmed the capability of the bump control to reduce buffet,
- Wind tunnel tests showed that the blowing jet device completely removes the shock unsteadiness,
- Numerical simulations using various computational approaches (RANS, URANS, LES) were successful in reproducing most of the experimental results, although slight discrepancies are found for the frequencies and the critical buffet conditions.

The existence of an unsteady shock dynamics in the laminar regime contrasts significantly with results obtained by Dor et al. in 1989 mentioned earlier that showed no sign of unsteadiness.

In terms of applications, important conclusions were given by the industrial partners of the project concerning the applicability and usefulness of the control concepts. It appears that control devices for laminar wings could promote smaller area wing concepts that would be beneficial in terms of viscous drag. However the overall benefit must be confronted with other sources of drag like wave drag, which may increase in this case of smaller wing area concept, and the necessity to power the control device in the blowing jet case (this not being the case for the “passive” bump device). The industrial partners further gave a series of recommendations

- The use of 2D experiments is valuable to understand the effectiveness of flow control devices allowing a down select of concepts for further study. However future experimental work investigating flow control to delay buffet should have experiments designed to output ΔC_l buffet due to flow control,
- Active flow control with blowing is effective at delaying buffet but integration at aircraft level needs to be investigated further regarding mass flow and power requirements,
- 3D wing studies should be undertaken on the most promising flow control devices. The wing planform should ideally not meet the buffet margin without flow control i.e. incorporate planform features only possible with buffet suppression,
- Investigate if the ONERA jet blowing buffet suppression flow control could help other flight phases i.e. improve high lift performance of high taper wing,
- Passive methods of reducing buffet are more favourable from the integration point of view but parasitic drag effects should be investigated,
- Buffet suppression flow control in the turbulent case was shown to enable high span wings in the WP1 of the Butterfli project. It is reasonable that this would still give benefit with a laminar wing.

WP3 Delaying laminar turbulent transition by controlling crossflow instability waves

Description of the methodology

Task 3.1 was devoted to preparatory numerical studies that provided guidelines for the design of the wind tunnel experiments, defined some basic properties and constraints for the actuator hardware and were used for the preselection of test conditions for the wind tunnel test campaigns. Moreover, preliminary volume force models that approximately describe the forcing by the DBD actuators had to be implemented into the numerical tools and cross-checked between the partners. ONERA, DLR, KTH, TsAGI and MIPT were involved in this task. The design of a suitable model setup for the T-124 w/t experiment and its manufacturing were done

by TsAGI within Task 3.2. This task was also devoted to the design of different actuator types, their manufacturing and preliminary testing, including a characterization of the flow field they induce, which was done by UNOTT and JIHT. The objective here was to optimize the actuator designs and to have a rather good understanding of the characteristics of each actuator design prior to their application in the T-124 and TRIN1 ('Juju') w/t experiments already. The actual testing of the actuators for laminar flow control was done in Task 3.3. In this task the detailed measurements on the actual effectiveness of the different actuation concepts and actuator designs were conducted, including detailed measurements on the resulting boundary-layer disturbance development. TsAGI and JIHT were in charge of the measurements performed in the T-124 wind tunnel, whereas ONERA conducted the TRIN1 experiments together with UNOTT for the experiments on VR-type actuation. The detailed numerical analysis of the experimental data was performed in Task 3.4. ONERA, DLR, KTH, AIRBUS UK, TsAGI, and MIPT were involved in this task using different numerical approaches. Since the experimental work ended later than originally planned additional parametric studies e.g. computations based on nonlinear parabolized stability equations (PSE) and secondary instability theory (SIT) were performed until the experimental data became available. Those studies provided additional insight about the sensitivity of the results towards changes in the actual conditions of the experiments. Moreover, e.g. the strength of the forcing of the VR-type actuation for the TRIN1 setup was varied systematically in direct numerical simulations in order to estimate the amount of forcing needed by this type of actuation for a successful transition delay. The synthesis of the achievements, the assessment of potential and limitations of the control concepts and actuator designs tested as well as recommendations for future work and application was done in Task 3.5, set out as a common activity of all WP3 partners lead by the industrial partners and the WP3 manager.

It was a priori known that the attempt to delay laminar-turbulent transition of swept-wing boundary layers by DBD plasma actuators will be a challenging task with significant risk. Therefore, the following risk mitigation strategy had been implemented in the work plan:

- Two different concepts of laminar flow control were considered.
- For each concept two different actuator designs were tested, developed by different project partners.
- The tests were performed in two different wind tunnels using different w/t model setups.

Description of the WP results

Two different sets of wind tunnel experiments were used for the studies on laminar-turbulent transition delay of swept-wing boundary layers by dielectric barrier discharge (DBD) plasma actuators. For the ONERA TRIN1 wind tunnel a suitable reference experiment consisting of a swept ONERA D airfoil was available already (*Figure a*), whereas the second reference experiment had to be designed and built as part of the BUTERFLI project. For this second set of experiments in the TsAGI T-124 wind tunnel a swept flat plate model setup was chosen (*Figure b*). The quasi-three-dimensional boundary layer on the swept flat plate was achieved by a suitable favourable pressure gradient imposed by a contoured insert attached to the upper test section wall. Additional contoured inserts attached to the test section side walls were designed to approximately establish infinite swept wing conditions. Preparatory numerical studies were necessary for the layout of the model setup, the selection of suitable freestream conditions for the planned experiments, and the definition of some key parameters needed for the design of the actuators, in particular the VR-type actuators.

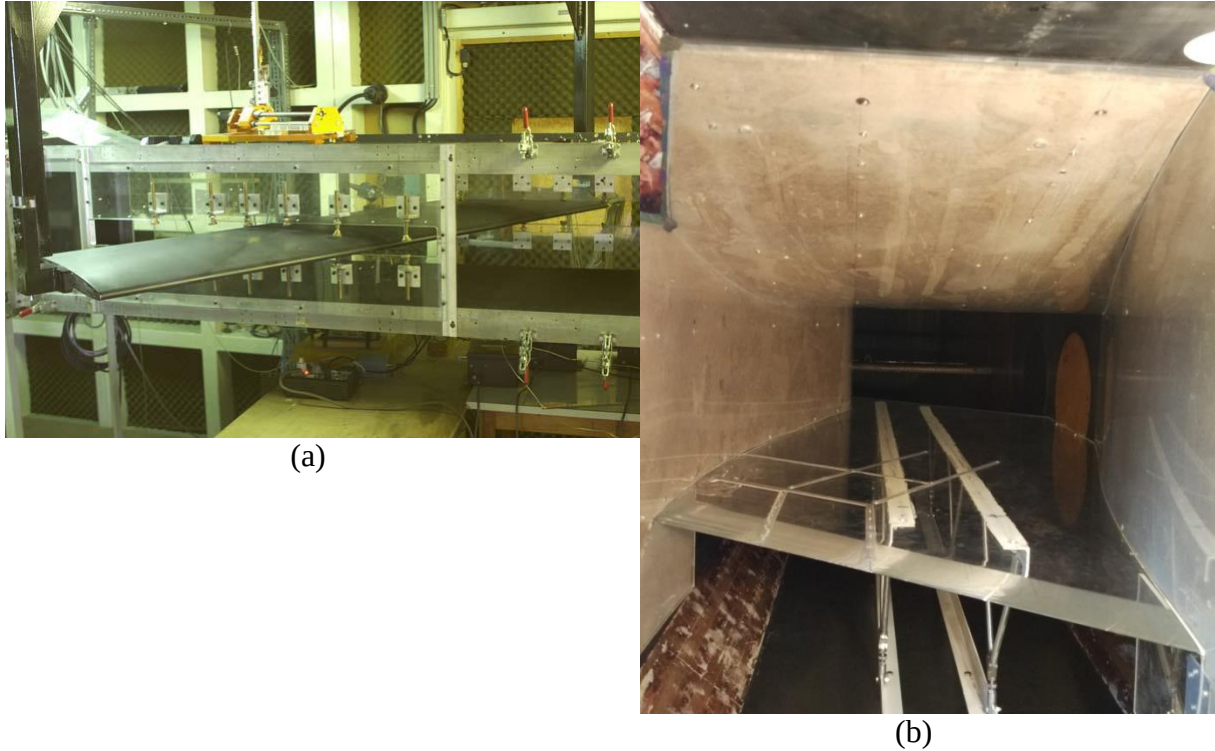


Figure 25. Photos of the two BUTERFLI wind tunnel model setups: (a) Swept ONERA D airfoil installed in the ONERA TRIN1 w/t. (b) Swept flat plate experiment in test section of TsAGI T-124 w/t together with the contoured inserts attached to the test sections wall.

A conventional design was used for the two actuators for crossflow velocity reduction. For the VR-type actuators two different concepts have been developed. The first concept is based on panwise inhomogeneous DBD with well-defined spanwise wavelength and was used in the T-124 wind tunnel experiments. The model insert with this sandwich-type actuator consists of a plastic body, a ceramic layer, exposed electrodes and a system of the buried grounded electrodes (*Figure*). The required spacing of the discharge filaments of 5 mm was achieved by an appropriate layout of the buried electrode which was manufactured as a printed circuit board. The exposed electrode was manufactured from a 20 μm copper or a 7 μm aluminum tape attached to the ceramic surface by a glue layer with typical thickness of 2-5 μm . The typical surface roughness of the ceramic plates was less than 2.5 μm . However, during the assembly steps with typical height of 20 μm may be formed. Additionally efforts to characterize the flow developing downstream of the actuator in a 2D boundary layer were made. The structure of the vortices was analyzed by particle image velocimetry (PIV) for two configurations corresponding to two sweep angles of the exposed electrode edge relative to the oncoming flow. The characterization of the induced flow field was performed in a Blasius boundary layer on a flat plate at a freestream velocity of 7 m/s. In the case actuator setup was inclined -relative to the oncoming flow co-rotating vortex filaments with a spacing of 5 mm develop as shown in *Figure* . Moreover, to estimate the effectiveness of crossflow vortex generation by sandwich actuators in the wind tunnel experiments an equivalent forcing model was developed. The model was derived using flow structure measurements in quiescent conditions and then was verified based on the resulting flow structure in a 2D boundary layer.

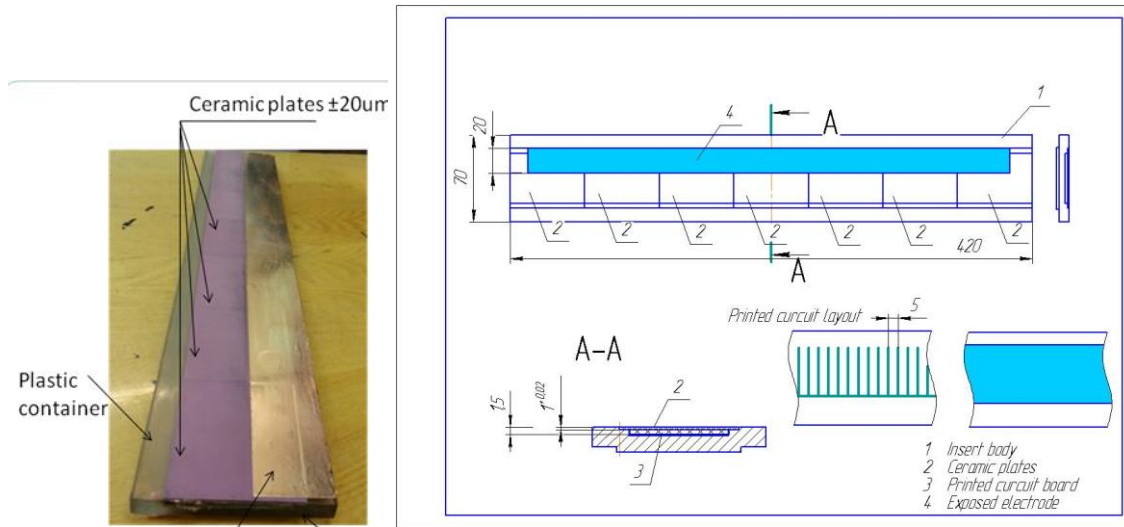


Figure 26. Photo of the actuator insert for the T-124 flat plate and a drawing of the actuator assembly

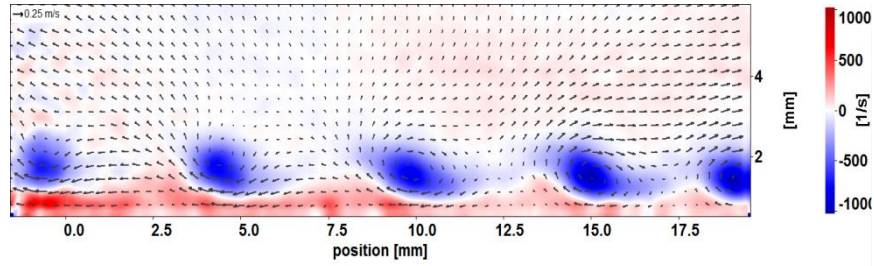


Figure 27. Flow field induced by the sandwich actuator from PIV measurements during preliminary tests.

The second concept is based on a row of equidistantly spaced DBD plasma actuation elements. Each of these elements produces an axisymmetric forcing component directed towards its symmetry axis. Therefore, a wall-normal micro jet is induced at the center of each of these elements. This VR-type actuator setup was used in the TRIN1 wind tunnel experiments. The specifications of the ring-type plasma actuators prepared are shown in *Table* , where the ‘GA’ actuator sheet was used for the 1st campaign, while the ‘P1’ actuator sheet was used for the 2nd and 3rd campaigns. All actuator sheets were made of a 0.15 mm thick Cirlex sheet. With the ‘GA’ actuator sheet, it was possible to test different VR spacings (either 3.5, 4, 4.5 or 6 mm) without reattaching the actuators sheet, meanwhile the constant 3.5 mm VR spacing was provided by the ‘P1’ actuator sheets. The plasma actuator sheet was attached to the airfoil by wrapping it around from the pressure side over to the suction side. The electrodes of the ‘GA’ actuator sheet are shown in *Figure* (a) and (b), while those of the ‘P1’ actuator sheet are shown in *Figure* (c) and (d). On installation to the airfoil, the four rows of actuator rings are located at $x/c = 1.9\%$, 3.3% , 4.7% and 6.1% . With these actuator sheets, we could simply connect the power supply to each row of ring actuator to test plasma actuators at different chordwise locations. Preliminary tests of this ring-type actuator design demonstrated that small wall-normal jets are induced. These tests were performed in quiescent air and the induced flow field was measured by PIV. The information from PIV on the velocity field induced could be used to estimate the corresponding volume force distribution. The force field data were used to model the effect of these VR-type actuators in subsequent direct numerical simulations.

Table 1. Specifications of the actuator sheets prepared.

Name	Spanwise Spacing (wave length) mm	No. of Actuator Rows	Ring Diameter (mm)	Qty.	Cirlex Dielectric Sheet		Campaign on test
					Size mm x mm	Thickness mm	
G4	4	1	1	1	297 x 400	0.15	-
G6	6	1	1	1			-
GA	3.5, 4, 4.5 and 6 (on one sheet)	4	1	3			1 st
P0.5	3.5	4	0.5	2	590 X 297		-
P1	3.5	4	1	2			2 nd , 3 rd

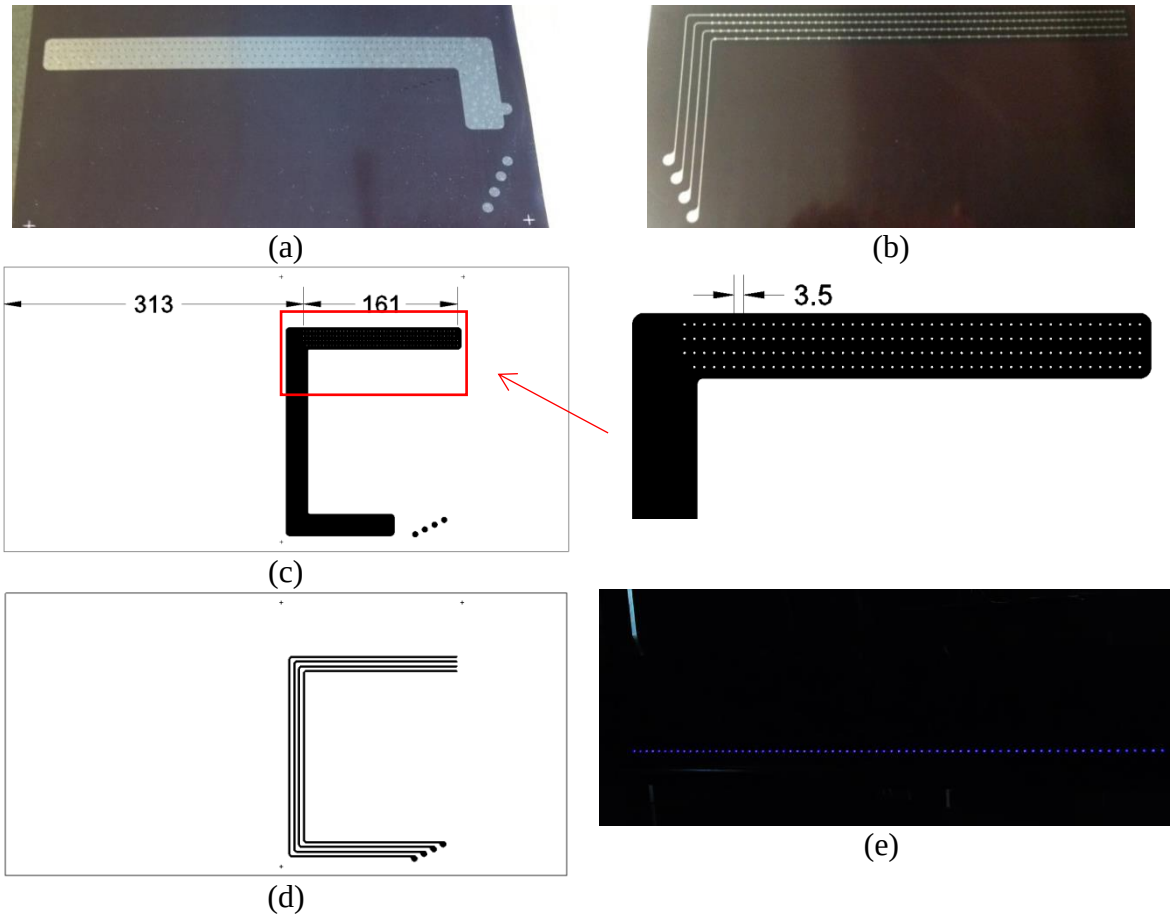


Figure 28. Photos of (a) the upper and (b) the lower (ground) surface of the 'GA' plasma actuator and drawings of (c) the upper and (d) the lower (ground) surface of the 'P1' plasma actuator. (e) A photo of glow discharges.

In the TRIN1 experiments the two-dimensional model based on an ONERA-D profile was mounted inside the test section at an angle of attack of $\alpha = -8^\circ$ normal to the leading edge and a geometric sweep angle of $\phi = 60^\circ$. The measurements were performed for a freestream velocity of $V_\infty = 70\text{m/s}$. Laminar-turbulent transition on the upper side of the model is driven by crossflow instabilities at these conditions.

For the first control strategy, the wind tunnel model was equipped with a single linear DBD actuator oriented in such a way that the induced body force is acting in the opposite direction of the crossflow component inside the boundary layer between $x/c=10\%$ and $x/c=20\%$ (see *Figure*, right). The goal was to reduce the steady crossflow component of the velocity in order to make the boundary layer more stable. In order to measure the transition location with a good spatial resolution, the hot-wire probe was moved along the chord of the model at a constant distance from the wall inside for boundary layer for a fixed free-stream velocity ($V_\infty = 70\text{m/s}$). For the baseline case (without actuation) the transition process started downstream $x/c=26\%$. With plasma actuation, the transition location progressively shifted upstream when the electrical power of the actuator was increased. This transition promotion seems to be independent of the unsteady effect induced by the actuator, since for a given power setting the transition location was nearly independent of the DBD signal frequency. During this campaign, the transition was promoted in all the cases where the plasma actuation was turned on.

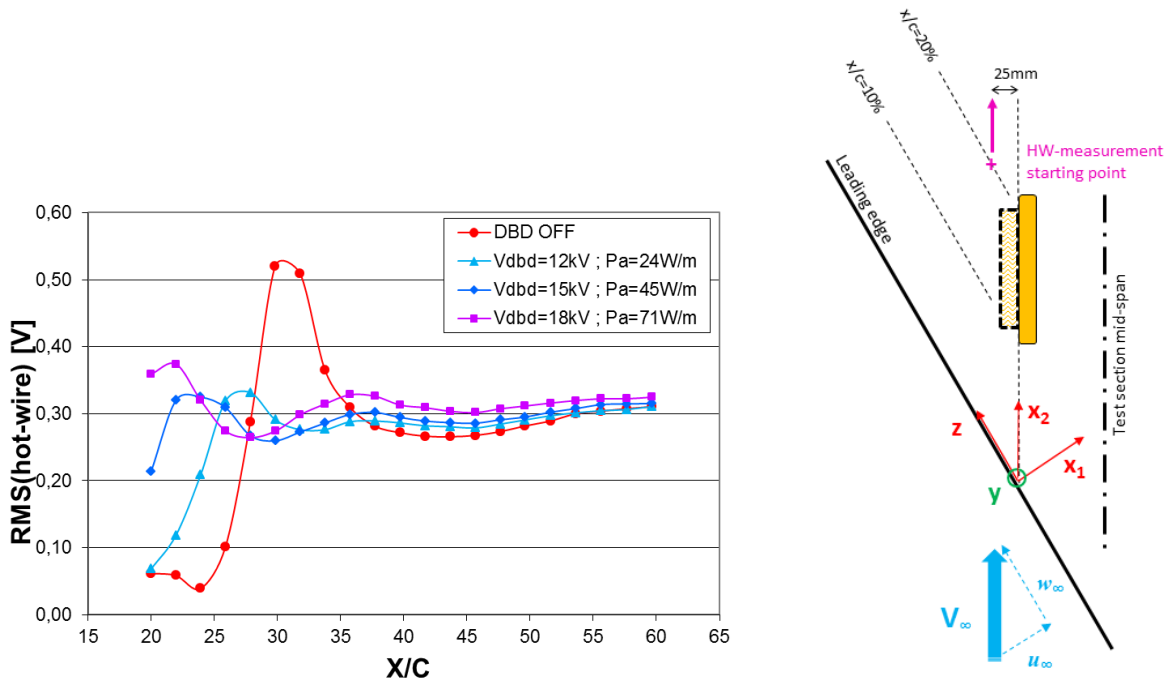


Figure 29. Evolution of the velocity fluctuations along the chord of the model with plasma actuation at a constant frequency $f_{DBD}=2\text{kHz}$ at $z=50\text{mm}$ (left) and location of the hot-wire measurement starting point (right).

For the second control strategy, crossflow instability control of the boundary layer over a swept ONERA-D airfoil was carried out using the virtual roughness (VR) based on an array of plasma actuators. Ring-type plasma actuators of various diameters, spanwise spacing and chord locations were operated at different forcing conditions in this investigation. Careful hot-wire measurements were carried out to investigate if the virtual roughness could delay transition to turbulence when the crossflow instability is the primary route for transition to turbulence. The wind tunnel results in the first test campaign clearly show that the VR promoted the crossflow instability wave of the same spanwise spacing, although the transition delay by the VR was not observed. Instead, the transition to turbulence was promoted by the VR in most test cases. These findings were confirmed by the measurements of mean velocity and turbulence intensity profiles as well as the time series of velocity fluctuations in the second and third test campaigns. Here, the energy spectra of velocity fluctuations showed the broad spectral peaks at around 3

kHz, whose downstream development was promoted by plasma forcing (*Figure*). We could not see clear indications of the secondary instability in any of the measurements. Therefore, we can conclude that the travelling waves would be interacting with the stationary waves in the transition process. This may explain why the VR was not successful in controlling the crossflow instability over a swept airfoil.

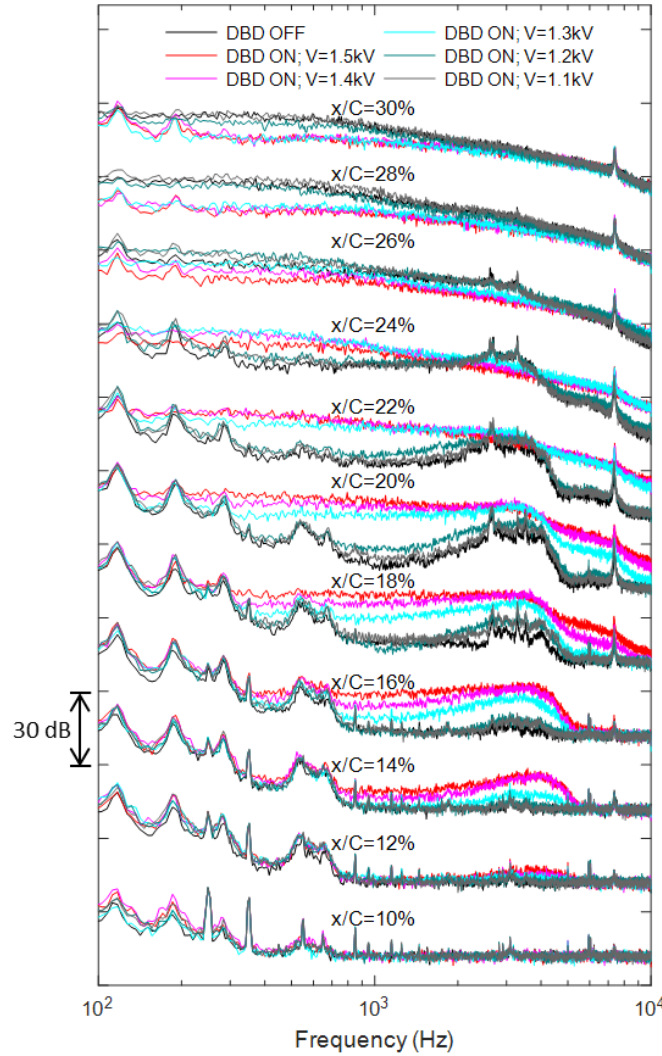


Figure 30. Power spectra of velocity fluctuations at different chord positions x/c . The spectra at the same location of x/c are plotted with the same reference level.

Different numerical studies on the linear and nonlinear disturbance development for the above experiments have been performed using local stability theory (LST), linear and nonlinear PSE, secondary instability theory and direct numerical simulations. E.g. the application of the ring-type plasma actuators for passive control of laminar-turbulent transition in a swept-wing boundary layer was investigated through direct numerical simulations. These actuators induce a wall-normal jet in the boundary layer and can act as virtual roughness elements. The flow configuration considered resembles the corresponding TRIN1 experiments. The actuators were modelled by the volume forces computed from the experimentally measured induced velocity field at the quiescent air condition. The natural surface roughness and unsteady perturbations were also included in the simulations. The interaction of the vortices generated by the actuators with these perturbations was investigated in detail. It is found that for a successful transition

control the power of the actuator should be increased to generate a jet velocity one order of magnitude higher than that in the considered experiments. A comparison of results of simulated flow field in case of natural transition, control with original plasma actuators and control with increased forcing of actuators is given in *Figure* .

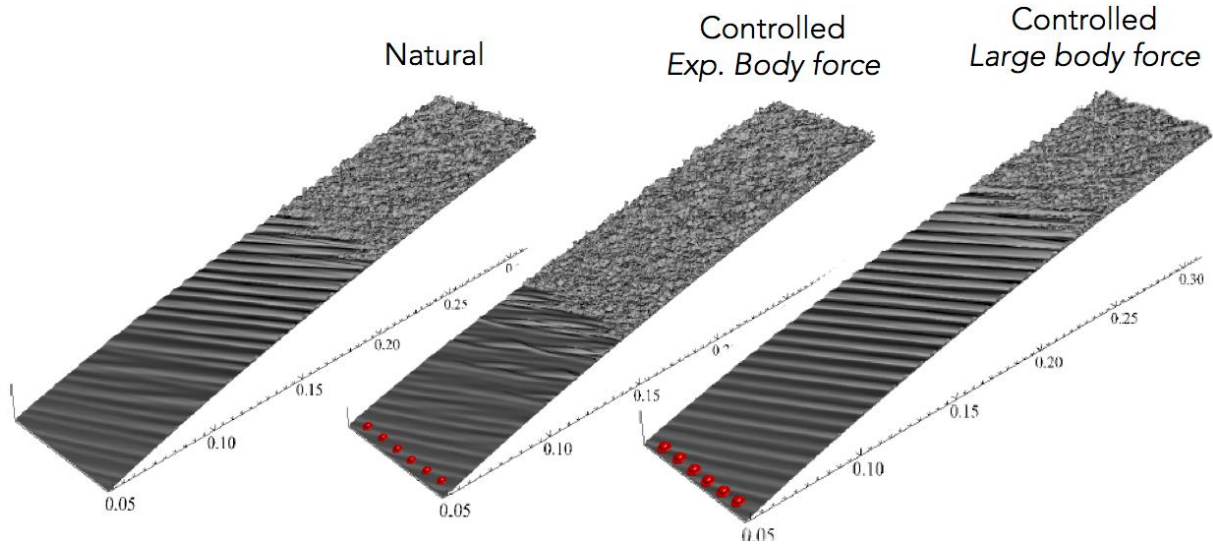


Figure 31. Visualization of simulated flow field in case of natural transition (left), control with original plasma actuators (middle) and control with increased forcing of actuators (right).

The experiments in the T-124 wind tunnel started with measurements for the reference configuration without any actuator. It could be shown that laminar-turbulent transition in the newly designed swept flat plate experiment was initiated by steady crossflow instability vortices. This is typical for low-turbulence environments. These tests hence confirmed that the setup was appropriate for the subsequent studies on control of crossflow-dominated laminar-turbulent transition by DBD plasma actuators.

The actuator for crossflow velocity reduction initiated a strong and almost sinusoidal boundary layer flow modulation with the period of the electrodes (*Figure a*), which was 10mm in the present experiment. This initiated additional growth of pulsations in minimums of tangential velocity and moved transition upstream. Oscillograms of the pulsations show that the discharge leads to the appearance of turbulent spots (*Figure b*). This effect possibly can be reduced in future by choosing a larger angle for the electrode inclination or by a further reduction of the period of the electrodes.

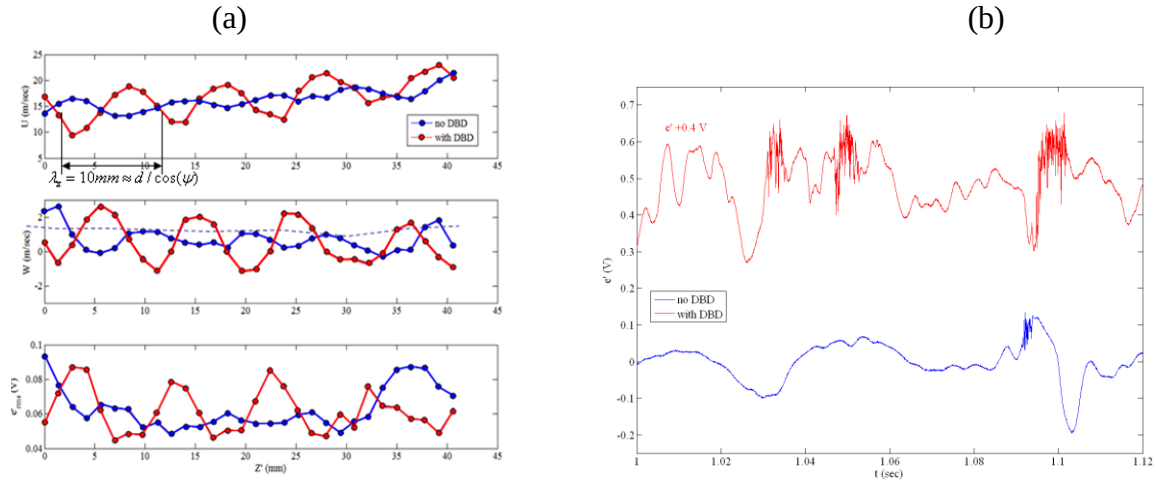


Figure 32. Influence of actuator for crossflow velocity reduction on laminar-turbulent transition: (a) spanwise variation of streamwise and crossflow mean velocity components and of the rms amplitude for a constant wall-normal distance above the plate and a chord position downstream of the actuator, (b) typical oscillograms of the velocity pulsations.

Investigations on the influence of the DRE-type actuator on the boundary layer showed that this actuator effectively generated a steady mode with the designed period of 5mm (*Figure a*). The amplitude of this mode is proportional to high voltage applied to electrodes of the actuator (*Figure b*). The amplitude of the induced short-periodic mode may be high enough for transition control. However, the discharge additionally generated velocity pulsations with a broadband spectrum in the boundary layer. These pulsations are also proportional to the amplitude of the high voltage initiating discharge, so the “signal to noise” ratio is independent from the applied voltage (*Figure b*). The spectra of pulsations in the boundary layer presented in *Figure* show that discharge-induced perturbations lead to enhanced growth of travelling crossflow instability modes with frequencies around 500Hz. This initiates earlier laminar-turbulent transition. A radical reduction of the amplitude of non-steady perturbations induced by DBD is necessary for a successful transition control by DRE-type actuators.

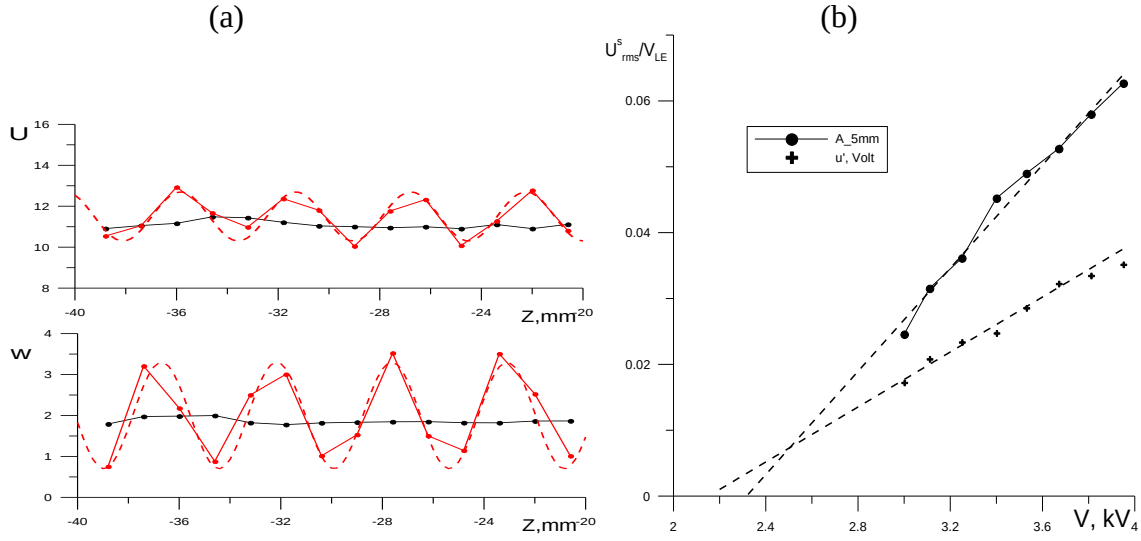


Figure 33. Horizontal profiles of tangential and crossflow velocity at a small distance downstream of the DRE-type actuator (a). Amplitude of generated "killer" mode and rms amplitude of the pulsations as function of the applied voltage (b).

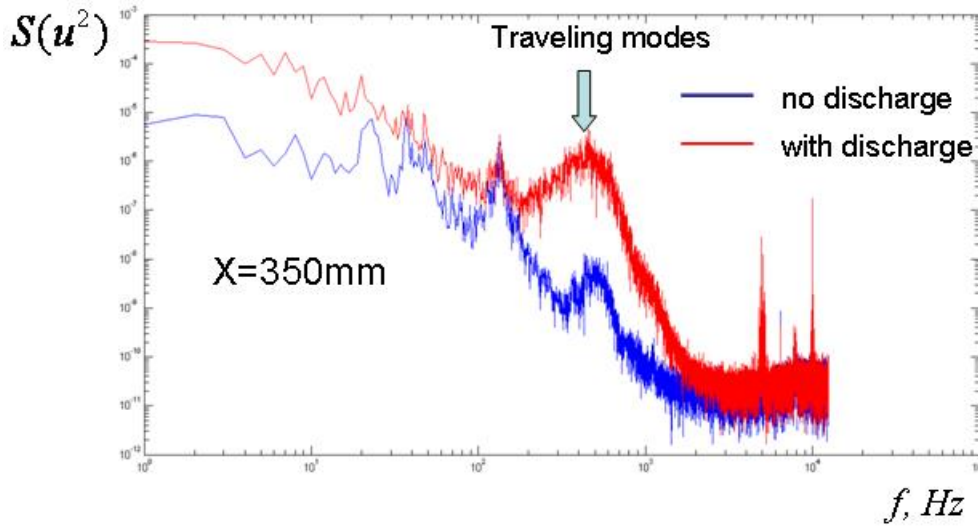


Figure 34. Comparison of the pulsation spectra without and with actuation.

Numerical modelling of the T124 swept plate tunnel test including control with DRE type plasma actuation has been performed using non-linear parabolized stability equations (PSE) to model the interaction of the target and killer modes. The experimental conditions corresponding to a virtual free-stream velocity of 31.9m/s were selected and a base flow for the stability analysis was obtained using a boundary layer solver subject to a C_p distribution taken from Navier-Stokes computations. Previous numerical studies had identified the most amplified (target) stationary crossflow mode to be of spanwise wavelength 7.5mm. The initial amplitude of this mode was set according to the requirement that the uncontrolled growth saturates in the vicinity of the observed transition. The initial amplitude of the killer mode was then modelled through a Linearised Navier Stokes (LNS) solver incorporating the body force model for plasma

actuation derived as part of the BUTERFLI project. A 5mm spanwise periodicity in the forcing corresponds to the periodicity of the actuators used in the experiment. This had been chosen because it generates a killer mode with the familiar 2/3 wavelength relationship with the target modes and non-linear analysis confirmed that it had a damping effect on the target mode. *Figure* shows the modelled modification to the base flow arising from the actuation and *Figure* shows the resultant 5mm crossflow disturbance in the vicinity of the actuator. The corresponding PSE computations indicate that the non-linear interaction between the killer and target mode results in a moderate delay in transition. A much larger control effect is observed for larger killer mode amplitudes but this cannot be achieved with this particular actuator configuration. In experiment, it was found that there was a forward movement of transition due to the introduction of travelling crossflow modes by the plasma actuator. This is not included in the current actuator model and cannot be predicted.

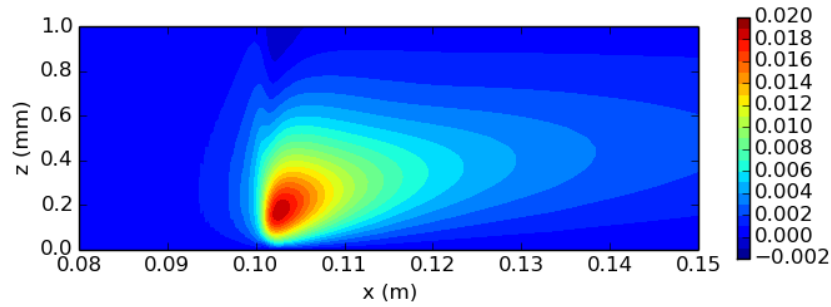


Figure 35. Base flow modification in vicinity of actuator due to plasma forcing

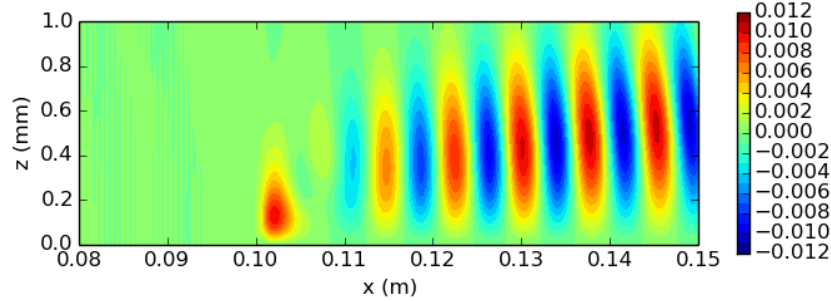


Figure 36. Stationary crossflow killer mode (real velocity component) generated in the vicinity of the plasma actuator

An assessment has been made of the drag reduction that can be achieved for a laminar wing on a short haul single aisle aircraft. From this an overall power saving has been calculated taking all factors into consideration including weight reduction due to lower fuel carrying requirements and structural changes. This power saving provides a limit for actuation power consumption if a net benefit is to be realised. This power consumption can be scaled to experimental conditions assuming constant efficiency and compared with the current power requirements of experimental plasma actuators. The indications from this are that DRE type actuation is much more likely to achieve a net benefit than a modified crossflow type actuation but even for the former the plasma actuators would have to be much more efficient than is currently the case to be viable at flight scale.

Global conclusions for the WP

The overall objective of delaying crossflow-dominated laminar-turbulent transition of swept-wing boundary-layers by DBD plasma actuators was not achieved within BUTERFLI, despite the multi-tier approach that had been implemented for risk mitigation. However, the project partners are not aware of any other successful attempt to delay swept-wing boundary-layer transition in literature up to now that uses this type of actuators. Nevertheless, most of the other more detailed objectives described above were achieved at least in part:

- A new model setup for crossflow-dominated transition studies in the TsAGI T-124 wind tunnel has been established. This setup will be available for other crossflow-dominated transition studies in future.
- Different DBD plasma actuator designs have been developed. These actuators will be available for future applications.
- Data on the flow field induced by the actuators were collected during the preliminary tests which could be used to improve the corresponding numerical models.
- The simulation capabilities for transition control by plasma actuators and other types of actuation have been further improved.
- The experimental results were analysed and compared to numerical predictions.
- A better understanding of the pros and cons of the different actuator designs has been established. In particular their current limitations with respect to the intended application have been identified. These provide the guidelines for further improvement of the designs and requirements for alternative actuator designs.
- The assessment of the drag reduction and of the overall power saving that can be achieved for a laminar wing of a short haul single aisle aircraft indicate that with a VR-type DBD plasma actuator it is more likely to achieve a net benefit than with a DBD plasma actuator for crossflow velocity reduction.

The following major lessons learnt concerning DBD plasma actuators for crossflow-dominated transition control are:

- A key issue of all present designs was the unwanted but significant promotion of unsteady boundary-layer instabilities. Unsteady boundary-layer instability modes were promoted even in cases where the nominal operational frequency provided by the power supply of the DBD plasma actuators was well above the frequency range of amplified boundary-layer instabilities. A major reduction of this unwanted unsteady forcing seems necessary.
- The spatial distribution of the induced forcing achieved by the actuators designed for transition control by crossflow velocity reduction may have been too inhomogeneous. Actually, they successfully promoted stationary crossflow vortices which is however unwanted in this particular flow control concept. Due to the working principle, there was a lower limit for the spacing of the electrodes of neighboring actuation elements which limited the spatial homogeneity of the forcing that was possible. Numerical studies that have been performed suggest that this problem may diminish for other angles between the electrodes and the boundary-layer edge streamline.
- The steady forcing of the VR-type actuator which was designed to produce wall-normal jets indeed induced the expected flow field. However, the experimental results of the actual wind tunnel experiment suggest that the forcing was too small for the current

application. Numerical studies indicated that an order of magnitude stronger forcing would have been needed. The VR-type actuator design based on spanwise inhomogeneous discharge successfully promoted stationary crossflow vortices at the expected wavelength and with significant amplitudes but as all other designs suffered from additionally promoted unwanted unsteady disturbances of too high amplitude.

There were major delays concerning the wind tunnel measurements, among others caused by a technical problem with the wind tunnel itself, a damage of the model which had to be repaired and the limited availability of key personnel. Therefore, the different measurement campaigns had to be rescheduled several times and moreover an extension of the project by 6 months was necessary. On the other hand, the delayed start of the wind tunnel campaigns left more time for preliminary tests of the different actuator designs and their improvement. Due to the late availability of experimental data the numerical studies had to be re-planned with more focus on parametric studies and less detailed comparisons with the experimental data. Nevertheless, all milestones were finally achieved and all planned deliverables were provided, though with some delay.

The results achieved within WP3 were presented at the 6th European Conference for Aeronautics and Space Sciences (EUCASS 2015) by three papers. One paper was presented at the AIAA Scitech 2017 and two papers at the ERCOFTAC European Drag Reduction and Flow Control Meeting (EDRFCM 2017). Additionally, three papers will be presented at the 7th European Conference for Aeronautics and Space Sciences (EUCASS 2017) and more publications are to be expected.

1.4 Potential impacts of the project

1.4.1 Scientific impact

The friction drag on the swept wings of today's aircraft, with its turbulent boundary layer, represents a considerable part (15-20%) of the total aircraft drag. Two key phenomena are obstacles for the improvement of performance: **buffet** and **boundary layer transition**. BUTERFLI will have an impact on these two phenomena.

Buffet suppression flow control has been identified in the project to enable laminar flow wings with reduced wetted area. Flow control appears to offer some benefits to enable high span wings. It is reasonable that flow control would still give benefit with a laminar wing.

Different plasma actuators tested for turbulent buffet control did not show real efficiency for alleviating it.

About boundary layer control, and crossflow control plasma actuators seems much more promising and research efforts have to be continued on type of control.

Passive control as 3D bumps for reducing buffet is more favourable from the integration point of view but parasitic drag effects should be investigated.

3D wing studies should also be undertaken on the most promising flow control devices.

From a general point of view, the project has consolidated a scientific community, gathering researchers from the academic world and industrial engineers, around the issues of buffet and boundary layer transition.

The project has produced scientific knowledge through technical reports and scientific publications.

1.4.2 Socio-economic impact

At project level, twelve European and Russian partners, coming from research institutes and from aeronautics industry, have maintained regular and lively technical and scientific exchanges throughout the project.

This collaborative project was marked by the overcoming of possible cleavages as, researchers / engineers, European / Russian geopolitical actual context, public institution / industry.

On long term point of view, augmentation of performance will lead to the reduction of fuel consumption, giving more competitiveness to airlines companies.

1.4.3 Environmental impact

At project level, this low TRL project lays and consolidates the foundations of a scientific knowledge basis without which it will be difficult to evolve towards a new generation of aircraft that consume less fossil energy.

At mid term, on turbulent supercritical airfoils, the buffet alleviation and the increase of buffet margin would allow to decrease drag for a given lift or to increase lift for a constant drag.

At longer term, smart laminar wing should constitute a potential of 10% aircraft total drag reduction, which leads to 10% lower fuel consumption in cruise conditions, and to the reduction of aeronautical transport carbon foot print.

1.4.4 Wider societal implications of the project

This collaborative project, bringing together a small number of partners, is a model of project to be promoted for the advancement of knowledge.

Moreover, this project, involving Russian and European (Schengen or not), and whose scientific results are quite remarkable, is a mark of optimism or hope for society in the broad sense.

This project is, of course, only a beginning to ensure that future air transport modes, short-medium- and long-haul, be more efficient and less polluting.

1.4.5 Dissemination and exploitation activities

Production of scientific knowledge through technical reports and scientific publications, in particular in the following international conferences EUCASS 2015 and EUCASS 2017.

Investigation of buffet control on transonic airfoil by tangential jet blowing	Abramova K.A.	MIPT TSAGI	Abramova K.A. Brutyan M.A. Lyapunov S.V. Petrov A.V. Potapchik A.V. Ryzhov A.A. Soudakov V.G.2
ARTIFICIAL STRUCTURES IN BOUNDARY LAYER AND THEIR APPLICATION FOR TRANSONIC SEPARATION CONTROL	Andrey Sidorenko	ITAM	Andrey Sidorenko Alexey Budovsky Pavel Polivanov
Study of structure and dynamics of gaseous jet after surface spark	A. A. Firsov		
Analytical and Numerical Estimation of the Body Force and Heat Sources Generated by the Surface Dielectric Barrier Discharge Powered by Alternating Voltage	V.R. Soloviev	MIPT JIHT	V.R. Soloviev V.M. Krivtsov
Experimental analysis of the shock-boundary layer interaction on a transonic laminar airfoil at $Re=3.106$	V. Brion	ONERA	V. Brion J. Dandois
NUMERICAL OPTIMIZATION OF BUFFET ALLEVIATING THREE-DIMENSIONAL SHOCK CONTROL BUMPS	Rouven Mayer	USTUTT	Rouven Mayer Thorsten Lutz Ewald Krämer
Stabilizing a Blasius boundary layer with Dielectric Barrier Discharge plasma actuation : experimental characterization and numerical modeling.	Natacha Szulga	ONERA	Natacha Szulga Olivier Vermeersch Maxime Forte Grégoire Casalis
Action of multiple-electrodes DBD actuators on the boundary layer. Theory and experiment	M.V. Ustinov	TsAGI	D.A. Russianov M.V. Ustinov A.A. Uspensky A. Yu. Urusov
THE STRUCTURE OF THE DIELECTRIC BARRIER DISCHARGE AND ITS EFFECT ON THE DISCHARGE-INITIATED GASDYNAMIC DISTURBANCES	Moralev Ivan	JIHT	Moralev Ivan Bityurin Valentin Sherbakova Victoria Kazansky Pavel Efimov Alexander

Two peer-reviewed publications in EUCASS BOOK SERIES Progress in Flight Physics Vol. 9:

Progress in Flight physics. Vol. 9 / [Edited by D. Knight, Y. Bondar, I. Lipatov, and Ph. Reijasse]. Moscow: TORUS PRESS, 2017. i 592 p., ill. 385.
(EUCASS advances in aerospace sciences book series)

ISBN 978-5-94588-215-7

EUCASS 2017 (Milano, July 2017)

Buffet delay on transonic airfoil by tangential jet blowing	SOUDAKOV Vitaly	TsAGI	RUSSIAN FEDERATION	Mr Vitaly SOUDAKOV Ms Ksenia ABRAMOVA Mr Murad BRUTYAN Mr Kamil KHAIRULLIN Mr Albert PETROV Mr Alexander POTAPCHIK
Localized micro-discharges group DBD vortex generators- disturbances source for active transition control	MORALEV Ivan	JIHT	RUSSIAN FEDERATION	Mr Ivan MORALEV Mr Valentin BITYURIN Ms Viktora SHERBAKOVA Mr Igor SELIVONIN Mr Alexander FIRSOV Mr Maxim USTINOV
Buffet suppression by submicrosecond spark discharge	FIRSOV Aleksandr	JIHT	RUSSIAN FEDERATION	Mr Aleksandr FIRSOV Mr Yuriy ISAENKOV Mr Ivan MORALEV Mr Sergey LEONOV Mr Vitaly SOUDAKOV
Transonic buffet control by plasma actuator with spark discharge	SIDORENKO Andrey	ITAM	RUSSIAN FEDERATION	Mr Andrey SIDORENKO Mr Anatoly MASLOV Mr Alexey BUDOVSKY Mr Oleg VISHNYAKOV Mr Pavel POLIVANOV
Laminar Buffet And Flow Control	BRION vincent	ONERA	FRANCE	Mr Vincent BRION Mr Julien DANDOIS Mr Laurent JACQUIN
Suppression of laminar SWBLI separation by spark discharge at low supersonic Mach number	SIDORENKO Andrey	ITAM	RUSSIAN FEDERATION	Mr Andrey SIDORENKO Mr Pavel POLIVANOV Mr Anatoly MASLOV
Effective Plasma Buffet and Drag Control for Laminar Transonic Airfoil	POLIVANOV Pavel	ITAM	RUSSIAN FEDERATION	Mr Pavel POLIVANOV Mr Andrey SIDORENKO Mr Anatoly MASLOV
Stabilization of Crossflow Instability with Plasma Actuators: Linearized Navier Stokes Simulations	ASHWORTH Richard	AIRBUS GROUP	UNITED KINGDOM	Mr Richard ASHWORTH Mr Kean Lee KANG Mr Shahid MUGHAL
Experimental study of cross-flow dominated transition control by dielectric barrier discharge	USTINOV Maksim	TsAGI	RUSSIAN FEDERATION	Mr Maksim USTINOV Mr Dmitry SBOEV Mr Ivan MORALEV Mr Sergey BARANOV
Direct numerical simulations of transition control in a swept-wing boundary layer using ring-type plasma actuators	HANIFI Ardeshir	KTH	SWEDEN	Mr Nima SHAHRIARI Mr Matthias KOLLERT Mr Ardeshir HANIFI

1.4.6 Contact details and website

BUTERFLI was coordinated by **two coordinators**: ONERA and TSAGI. The European Coordinator (ONERA) was the legal entity acting as the intermediary between the Partners and the European Commission. The Russian Coordinator (TSAGI) was the legal entity acting as the intermediary between the Partners and the Ministry of Industry and Trade of Russian Federation. The persons mandated by ONERA and TSAGI as coordinators were Philippe Reijasse and Sergey Lyapunov. Their roles were fundamental to the project management.

As the decision-making body of the Consortium, the **Steering Committee** approved the strategic roadmap and the general outline of the project. It was chaired by ONERA and TSAGI and was composed of the representatives of the partners:

Steering Committee Members		
Partner	Technical matters	Administrative/financial matters
ONERA	Philippe Reijasse	Jean-Michel Goulon
TsAGI	Vitaly Soudakov	Yulia Shamaeva
DLR	Stefan Hein	Sylke Heinlein
AIRBUS	Stephen Rolston	Shaun Griffiths
ERDYN	Pinar Temel	Pinar Temel
USTUTT	Thorsten Lutz	Thorsten Lutz
KTH	Hanifi Ardeshir	Heide Hornk
UNOTT	Kwing-So Choi	Paul Cartledge
ITAM	Andrey Sidorenko	Anatoly Maslov
JIHT	Sergey B. Leonov	Vladimir A. Zeigarnik

The **Work Package Leaders** were responsible for the overall work done in their Work Packages:

WP1	TsAGI	Vitaly SOUDAKOV
WP2	ONERA	Vincent BRION
WP3	DLR	Stefan HEIN
WP4	ONERA	Denis SIPP
WP5	ONERA	Philippe REIJASSE

Furthermore, the website of BUTERFLI was online at the following address: www.buterfli.eu. Its objective was to raise awareness about the BUTERFLI project and EU funding and keep informed the Scientific Community with news section and public documentations. At the end of the project, the contract for hosting the website was terminated.