**UNIVERSIDADE DE SÃO PAULO
ESCOLA DE ENGENHARIA DE SÃO CARLOS**

Gabriel Pereira Gouveia da Silva

**Atuadores de plasma de descarga de barreira dielétrica
aplicados a dispositivos hipersustentadores para redução
de ruído aerodinâmico**

São Carlos

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SÃO CARLOS SCHOOL OF ENGINEERING**

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*To all those who suffer from exposure to aeronautical noise.
May this work contribute to the improvement of their life qualities.
To all my relatives, friends and teachers, who encouraged me
and contributed, each in his own way, so that I could get here.*

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*“But the student will find that experience is the best teacher.
The reason why I get along with comparative ease now is because
I know from experience the enormous number of things that
won’t work. For instance, I start on a new invention tomorrow.
From the great number of experiments I have made, and the
vast amount of information I have stored up, I am saved a great deal
of time and trouble in not having to travel over barren ground.”*

Thomas A. Edison

ABSTRACT

SILVA, G. P. G. **Dielectric barrier discharge plasma actuators applied to high-lift devices for aerodynamic noise reduction**. 2019. 139p. Dissertação (Mestrado) - São Carlos School of Engineering, University of São Paulo, São Carlos, 2019.

Since the 1970s, when the reaction engines had their noise reduced by the increase in their bypass ratio, airframe became the most prominent aerodynamic noise source during the approach to landing. From the airframe noise sources, the high-lift devices are one of the most significant. The most studied and applied solutions for these noise sources refer to passive flow control, and there are relatively few studies related to active flow control. Active flow control is achieved by adding energy to the flow in order to manipulate it. One way to accomplish this is through the dielectric barrier discharge plasma actuators. These devices create an intense electric field between two electrodes separated by a dielectric. This strong electric field ionizes and accelerates the air through collision of charged particles of the plasma with neutral air molecules. Thus, a wall jet is produced without using moving parts. In this research, plasma actuators were installed at the flap side edge, at the cove and at the cusp of the slat. Wind tunnel tests have demonstrated the potential of these devices for high-lift noise reduction, allowing for a decrease up to 0.75 *dB* in the overall flap noise and up to 3.3 *dB* in overall slat noise (with a reduction of 12 *dB* at the higher peak).

Keywords: Plasma actuator. Dielectric barrier discharge. Flap noise. Slat noise. Airframe noise. Active flow control.

RESUMO

SILVA, G. P. G. **Atuadores de plasma de descarga de barreira dielétrica aplicados a dispositivos hipersustentadores para redução de ruído aerodinâmico**. 2019. 139p. Dissertação (Mestrado) - São Carlos School of Engineering, University of São Paulo, São Carlos, 2019.

Desde a década de 1970, quando os motores a reação tiveram seu ruído reduzido devido ao aumento da razão de derivação, o ruído de célula se tornou o mais proeminente durante a fase de aproximação para pouso. Do ruído de plataforma aeronáutica, destacam-se os ruídos gerados pela interação do escoamento com os dispositivos hipersustentadores. As soluções mais estudadas e aplicadas para estas fontes de ruído se referem a controle passivo do escoamento, havendo relativamente poucos estudos relacionados a controle ativo. Controle ativo do escoamento é obtido adicionando-se energia ao mesmo, e uma forma de realizar isto é através dos atuadores de plasma de descarga de barreira dielétrica. Nestes dispositivos um intenso campo elétrico entre dois eletrodos separados por um dielétrico é gerado, ionizando e acelerando o ar através da colisão de partículas carregadas do plasma com moléculas neutras. Desta forma, um jato de parede é produzido sem o uso de partes móveis. Nesta pesquisa, atuadores de plasma foram instalados na borda lateral do flape, na cova e na cúspide do eslate. Ensaios em túnel de vento demonstraram o potencial destes dispositivos para redução de ruído de hipersustentadores, permitindo a redução de até 0.75 dB no ruído global de flape e de até 3.3 dB no ruído global de eslate (com redução de 12 dB no maior pico).

Palavras-chave: Atuador de plasma. Descarga de barreira dielétrica. Ruído de flape. Ruído de eslate. Ruído de plataforma aeronáutica. Controle ativo de escoamentos.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABS	Acrylonitrile butadiene styrene
AC	Alternating current
ACARE	Advisory Council for Aeronautics Research in Europe
ANAC	Agência Nacional de Aviação Civil (National Civil Aviation Agency)
CAEP	Committee on Aviation Environmental Protection
CFD	Computational fluid dynamics
CFR	Code of Federation Rules
CNPq	Conselho Nacional de Desenvolvimento Científico e Tecnológico (National Council for Scientific and Technological Development)
CS	Certification Specifications
CSM	Cross spectral matrix
DBD	Dielectric barrier discharge
DBD-PA	Dielectric barrier discharge plasma actuator
DC	Direct current
D.C.	Duty cycle
EASA	European Aviation Safety Agency
EESC	Escola de Engenharia de São Carlos (São Carlos School of Engineering)
EHD	Electrohydrodynamics
FAA	Federal Aviation Administration
FFF	Fused filament fabrication
FINEP	Financiadora de Estudos e Projetos (Funding Authority for Studies and Projects)
FIPAI	Fundação para o Incremento da Pesquisa e do Aperfeiçoamento Industrial (Foundation for the Enhancement of Research and Industrial Improvement)

FTP	File transfer protocol
HFHVPS	High-frequency/high voltage AC power supply
HDF5	Hierarchical data format 5
ICAO	International Civil Aviation Organization
IEPE	Integrated electronics piezo-electric
I/O	Input/output
LAE	Laboratório de Aerodinâmica Experimental (Laboratory of Experimental Aerodynamics)
LQG	Linear–quadratic–Gaussian
OASPL	Overall sound pressure level
OUAGDP	One Atmosphere Uniform Glow Discharge Plasmas
PA	Plasma actuator
PIV	Particle image velocimetry
PID	Proportional–integral–derivative controller
PLA	Polylactic acid
PSD	Power spectral density
PWM	Power width modulation
RBAC	Regulamento Brasileiro de Aviação Civil (Brazilian Civil Aviation Regulation)
RMS	Root mean square
USP	University of São Paulo

LIST OF SYMBOLS

C_p	Pressure coefficient
F	Frequency of the output modulation
f	Frequency of the AC voltage applied to the DBD-PA
h	Dielectric thickness
L/D	Lift-to-drag ratio
M	Mach number
Re	Reynolds number
R^2	Coefficient of determination
St	Strouhal number
U	Velocity in the x direction
V_{in}	HFHVPS Voltage input
V	HFHVPS Voltage output
x	Streamwise direction of the straight DBD-PA
y	Spanwise direction
z	Height direction from the DBD-PA surface
α	Angle of attack
ε	Dielectric constant

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1 INTRODUCTION

In order to operate, each civil aircraft must pass the noise certification. The noise limits established by regulatory agencies must be respected in all phases of the flight. In Brazil these limits are defined by the National Civil Aviation Agency (ANAC) through the RBAC 36 (AGÊNCIA NACIONAL DE AVIAÇÃO CIVIL, 2009), which fully adopts the text of the 14 CFR Part 36 (FEDERAL AVIATION ADMINISTRATION, 2006), the USA Federal Aviation Administration (FAA) document. In Europe, similar standards are set by the European Aviation Safety Agency (EASA) through the CS-36 (EUROPEAN AVIATION SAFETY AGENCY, 2016). All these regulations are compatible with the standards defined by ICAO (International Civil Aviation Organization) in the Annex 16 of the Chicago Convention. (INTERNATIONAL CIVIL AVIATION ORGANIZATION, 2011).

Due to urban growth (which increasingly brings urbanized areas closer to major airports), to growing air fleets and increasing aircraft operations, noise from airport activities has negatively impacted an increasing number of people, leading to a growing restriction on acceptable levels of noise by the authorities (SMITH, 2009), as shown in Figure 1. Thus, noise certification regulations are constantly updated to meet the requirements of the Committee on Aviation Environmental Protection (CAEP). The last CAEP report (INTERNATIONAL CIVIL AVIATION ORGANIZATION, 2016) sets a reduction target of 10 *dB* in the aeronautical noise level per operation by 2020 compared to 2000 levels. This guideline is based on the Advisory Council for Aviation Research and Innovation in Europe (ACARE) directives, which set this target in 2001 (BUSQUIN et al., 2001).

Figure 1: Progression of the ICAO Noise Standard

Source: INTERNATIONAL CIVIL AVIATION ORGANIZATION (2016)

Until the 1970s aeronautical noise was predominantly generated by the reaction engines, but this noise source is constantly being reduced with the increase in the bypass ratio of these engines. So, in phases of flight when the engine operating power is low (during approach to landing), airframe noise has become dominant (Figure 2). Airframe noise is generated by the interaction of instabilities of the external turbulent flow with the surfaces of the aircraft exposed to the flow (like empennage, fuselage, fairings, landing gear and high-lift devices such as slats and flaps) (ZAPOROZHETS; ATTENBOROUGH; TOKAREV, 2011).

Figure 2: Noise component breakdown of a commercial aircraft

Source: Airbus (201-)

Noise generated on the flap side edge and slat cove are among the most prominent airframe noise sources in the approach and landing phases. The solutions currently applied to these noise sources are based on passive flow control. One of these forms of passive control, for example, is the use of cove fillers, which fill the cavity of the extended slat, considerably reducing flow instabilities and consequently noise (SCHOLTEN et al., 2016). In the case of the flap, porous tips or flexible connections to eliminate the discontinuity between the wing and the flap edge (KHORRAMI et al., 2016) may be used. However, these solutions can be mechanically complex, heavy and difficult to manufacture and maintain.

Active control is obtained when the manipulation of the airflow is made by adding energy to it. One way to accomplish this is using dielectric barrier discharge plasma actuators (DBD-PA). DBD-PAs are devices that ionize the air in their vicinity, creating an atmospheric cold plasma discharge that is accelerated by the electrical field, transferring momentum to the surrounding air through collision of ions with neutral molecules (WANG et al., 2013). This results in a air jet in the order of up to 10 m/s close to the wall, called ionic wind or ionic blow. Such devices have the advantages of operating at low

electrical power without requiring moving parts, pneumatic or hydraulic systems, thus being lightweight and having fast response (MOREAU, 2007). These devices also have a thin thickness that almost do not interfere with the flow when the DBD is deactivated (MOREAU, 2007).

A stall delay application of DBD-PA was explored by He, Corke and Patel (2009). Since the plasma actuator installed on the leading edge of the wing keeps the flow attached at high angles of attack, it could replace the complex and heavy retraction and extension mechanisms of flaps and slats, which is especially advantageous in aircraft design, where light and simpler structures are preferable, along with the elimination of the high-lift noise problem (HE; CORKE; PATEL, 2009). Although the work of He, Corke and Patel (2009) is conceptually interesting and presents significant results, the idea would hardly be applicable in commercial aircraft, since it would be difficult for certification due the risk of stall at low altitudes, causing a catastrophic accident in case of DBD-PA failure during approach to landing. Furthermore, in the current state of technology, plasma actuators have little control authority under actual flight conditions, since the energy they introduce is very small relative to the energy of the free flow to be manipulated. The traditional flap and slat systems are quite consolidated and reliable, being preferable in the development of a new aircraft. Thus, it is more interesting to find a solution that combines traditional high-lift devices with plasma actuators to attenuate their noise, so as not to compromise flight safety, being a commercially certifiable solution.

Yong, Xunnian and Dejiu (2013) mention a concept proposed by research groups from the University of Notre Dame and Airbus Noise Technology Center in which a combination of flap rounded tip and plasma actuators could guide the tip vortices away from the flap side edge, thereby reducing noise. However, to date, it was not found in the literature the development of this concept. Thus, in the chapter 4 of the present work, a concept similar to that mentioned by Yong, Xunnian and Dejiu (2013) was developed and tested in wind tunnel. The difference here is that the DBD-PAs were used not to blow the vortex away from the flap, but to generate a counter vortex in combination with the flap rounded tip.

Chen et al. (2013) used plasma actuators together with traditional slats to minimize the tonal peaks of the slat sound spectrum. The work developed by these researchers consisted of an experimental investigation on traditional DBD actuators installed along the slat cusp, operated by an LQG (Linear-Quadratic-Gaussian) controller. The researchers obtained 20 *dB* reduction in the dominant tonal peak. According to Chappell et al. (2012), the work of Chen (2012) is to date the only one in the literature that reports the reduction of slat noise through the use of dielectric barrier discharge, which is confirmed until now by searches in the databases Web of Science, Scopus and Google Scholar. However, the region of plasma actuator application in the work of Chen et al. (2013) was only the slat

cusps. This way, their results were mainly suppression of the tonal components of slat noise, with slight effect on broadband noise. Chen (2012) suggests in his doctoral thesis that future work be done with plasma actuators installed in more appropriate positions, such as on the suction surface of the slat or on the cove surface near the trailing edge of the slat. The chapter 5 of the present research was based on these indications, aiming to obtain an attenuation of the slat broadband noise through the installation of plasma actuators in the slat cove.

Therefore, in summary, the objective of this research was to investigate if dielectric barrier discharge plasma actuators can be used to reduce high-lift aerodynamic noise.

First, a literature review is presented, covering the high-lift noise problem and a discussion about the DBD-PA theory and applications. This review provided the theoretical basis and inspiration for the experimental work developed later. Then, a characterization of the DBD-PAs used along this research is presented. The following chapters present the experiments with flap and the slat, each one in its own chapter divided into experimental procedures and results sections. Lastly, some conclusions are stated and suggestions for future work are made.

2 LITERATURE REVIEW

In this chapter the theoretical basis of the research is presented. A literature review was carried out through searches in the Web of Science, Scopus and Google Scholar databases in order to better understand the problem of high-lift noise and the proposed solution of plasma actuators. This literature review aimed as well to map the state of the art in these themes, finding some gaps in it that this research aims to fill.

2.1 High-lift aerodynamic noise

Unsteady aerodynamics caused by geometrical discontinuities (like cavities, gaps and edges) is a significant source of noise called airframe noise (TURNER et al., 2013). When the engines are operating at low power, as during approach, the airframe sources are dominant. Among the sources of airframe noise, the high-lift devices and the landing gear are the most prominent. (SMITH, 2009; ZAPOROZHETS; ATTENBOROUGH; TOKAREV, 2011). Slat noise have frequencies up to 2500 Hz , with peaks in the rear arc, and flap noise have frequencies from about 4000 to 16000 Hz , with peaks in the forward arc at high frequencies and in the rear arc at low frequencies (GUO; JOSHI, 2003; SMITH; CHOW, 2003; KOPIEV; ZAYTSEV; BELYAEV, 2016), being both mainly broadband sources. In order to achieve the ACARE goals (BUSQUIN et al., 2001), the understanding of how noise is generated at this sources is fundamental. Without this knowledge, solutions cannot be well designed to reduce airframe noise. This section presents the governing mechanisms of the noise generation in high-lift devices.

2.1.1 Flap noise

An overview of the flap noise problem is given by Dobrzynski (2010). According to this author, the flap side edge is an important noise source when considering executive and regional aviation, whose some aircrafts do not have slats (DOBRZYNSKI, 2010).

The flap noise is generated by complex three-dimensional vortices (Figure 3): due to static pressure difference between suction and pressure surfaces of the flap, a primary vortex develops at the lower edge from the pressure to the suction side of the flap, near its leading edge; for the same reason, a secondary vortex develops from the flap upper edge to its suction side (MACARAEG, 1998; DROBIETZ; BORCHERS, 2006; DOBRZYNSKI, 2010). The lower vortices are continuously fed by the shear layer instabilities and are drawn by the flow to the upper surface, where both these vortices are merged and then separate from the pressure side at some position around 70% flap chord (MACARAEG, 1998; DROBIETZ; BORCHERS, 2006; DOBRZYNSKI, 2010). So, the flap side edge noise is a composition of classical leading edge noise mechanisms, pressure fluctuations caused

by vortex breakdown, interaction between vortices and surfaces or edges and accelerated free turbulence in the vortex flow (DROBIETZ; BORCHERS, 2006; DOBRZYNSKI, 2010; ROSSIGNOL, 2013). Therefore, flap side edge is mainly a broadband noise source where unsteady vorticity fluctuations from pressure side shear layer interacting with the upper tip edge produce mid-to-high frequencies, and vortex interaction with suction side surface after vortex merging produces low-to-mid frequencies (DROBIETZ; BORCHERS, 2006; ROSSIGNOL, 2013). According to Li and Liu (2017), besides this side edge noise mechanism, flap noise is also generated by interactions between the main element shear layer produced at the flap housing and the turbulent flow, flow separation, vortex shedding and mixing layer formed over the flap (Figure 4). The total noise radiated from flap is higher at higher flap deflection angles (GUO; JOSHI, 2003).

Figure 3: Flap side-edge noise generation mechanism

Source: Rossignol (2013)

Figure 4: Other sources of flap noise

Source: Li and Liu (2017)

Thus, the intensity of sound radiation depends upon the strength of the vorticity at the flap side edges and the distance of the vortex from the edges, and reducing tip

vortex can reduce noise radiated from flap tip (HARDIN, 1980).

Like other authors, Macaraeg (1998) and Streett et al. (2003) performed a series of numerical simulations and experiments with different techniques (steady and unsteady pressure measurements, hot films, oil flows, pressure sensitive paint, 5-hole probe, PIV, laser velocimetry, laser light sheet measurements and microphone array measurements) in order to investigate the main features of flap side edge noise generation, confirming the mechanism previously described. This approach of combining computational and experimental studies is a broadly used tool for understanding complex aeroacoustic problems. Drobietz and Borchers (2006) highlights that this complexity of high lift aerodynamics and noise generation mechanisms creates a difficulty in understanding and implementing scaling of the noise solutions developed.

Most of the solutions to the flap side edge noise are based on passive flow control, such as fences (DOBRZYNSKI; POTT-POLLENSKE, 2001; GUO; JOSHI, 2003; DROBIETZ; BORCHERS, 2006; KOPIEV; ZAYTSEV; BELYAEV, 2016) to reduce shear layer instabilities and avoid vortex merging; transparent edge replacements (foam, porosities and brushes) to reduce surface radiation efficiency and dissipate intruding turbulences (DROBIETZ; BORCHERS, 2006; DOBRZYNSKI, 2010; KHORRAMI et al., 2016); trailing edge serrations to reduce interaction of merged vortex with trailing edge (DROBIETZ; BORCHERS, 2006) and flexible link between flap edge and main element for a soft geometry transition (KHORRAMI et al., 2016). Active flow control, though, is proposed by some research groups from the University of Notre Dame and the University of Southampton (YONG; XUNNIAN; DEJIU, 2013). The concept proposed by these groups, presented by Yong, Xunnian and Dejiu (2013) in their review article, is based on a combination of plasma actuators with a rounded tip to produce a Coandă effect (Figure 5). Their intention is to blow the vortices away from the flap tip. However, apart from this review article, it was not found in the literature any other publication regarding this concept.

Figure 5: Concept proposed by a research group at the University of Notre Dame

Source: Yong, Xunnian and Dejiu (2013)

2.1.2 Slat noise

Whereas the flap side edge is considered a punctual sound source, the slat is a distributed source along a line. Considering the acoustic power radiated per unit area, the flap side edge is a more intense source than the slat. However, when integrated along its length, the slat contribution to overall noise is more significant than that of more intense punctual sources. Thus, during the approach to landing, slat noise is dominant at low and medium frequencies when compared to flap side edge noise (DOBRZYNSKI et al., 1998; KHORRAMI, 2003; CHOUDHARI; KHORRAMI, 2006).

Slat noise is a complex aeroacoustic problem whose governing mechanisms are not yet clearly understood (CHEN, 2012). This is due to the presence of independent noise generation mechanisms, in overlapping frequency bands (KHORRAMI, 2003). According to Dobrzynski et al. (1998), Imamura et al. (2009) and Dobrzynski (2010), slat noise can be classified into three overlapping components: broadband, which is the main source of slat noise (dominant in real flight conditions) and whose generation mechanisms are not yet fully understood; multiple tonal peaks of low frequency, related to the mechanism of acoustic feedback; and high frequency tones related to vortex shedding at the slat trailing edge (which does not occur in flight Reynolds, being a typical problem of scaled wind tunnel models).

Several studies aimed at mapping and understanding the flow in the slat region. These studies used an approach in which experiments and computational fluid dynamics (CFD) simulations complement each other, seeking an understanding of the mechanisms that lead to the noise emission. The flow structure within the slat cove is extremely complex, having characteristics dependent on the geometry, deflection angle, gap, overlap, flow velocity and angle of attack of the multi-element wing (JENKINS; KHORRAMI; CHOUDHARI, 2004; MA; ZHANG, 2009). The geometry of the slat is such that it allows, when stowed, to blend into the main element, eliminating surface discontinuities during cruise flight. However, when extended, the slat has a cove that generates a region of separation, in which instabilities and vorticity are generated and can interact with neighboring surfaces, generating noise (JENKINS; KHORRAMI; CHOUDHARI, 2004). According to Choudhari and Khorrami (2006) and Dobrzynski (2010), a vortex develops in the slat cove, driven by the flow that passes through the slot. Between this vortex and the undisturbed flow, a free and unstable shear layer develops originating at the cusp and impacting the surface of the cove (Figure 6).

Figure 6: Physical mechanisms of slat noise generation

Source: Choudhari and Khorrami (2006)

These instabilities that lead to slat noise are probably generated in the shear layer of the slat (PEREIRA et al., 2018). Khorrami (2003) demonstrated that this shear layer is an amplifier of low and medium frequency disturbances. This amplification occurs due to a feedback mechanism (CHOUDHARI; KHORRAMI, 2006; KHORRAMI; LOCKARD, 2006; CHOUDHARI; KHORRAMI, 2007; HUANG; LI; WANG, 2013): after passing through the cusp, the shear layer is wrapped in discrete spanwise vortices; these spanwise deformations are amplified with the downstream distance, resulting in predominantly three-dimensional vortical structures; the vortices approaching the shear layer reattachment region are strongly three-dimensional, and when interacting with the trailing edge, are distorted and broken in other vortices; a significant fraction of these vortices are strongly accelerated in the direction of flow, interacting with the trailing edge; the remaining vortices are trapped in the recirculation zone, being convected back to the cusp; this convection of three-dimensional vorticities trapped into the shear layer induces non-stationary eruptions of secondary vorticity along the boundary layer of the surface of the slat cove; the vortices that go to the slat cove end up reaching the cusp and further disturbing the shear layer, closing the feedback loop. This mechanism is similar to that of a cavity flow (ROGER; PERENNES, 2000; TAKEDA; ZHANG; NELSON, 2002; TERRACOL; MANOHA; LEMOINE, 2016). According to Jenkins, Khorrami and Choudhari (2004), Choudhari and Khorrami (2007) and Lockard and Choudhari (2009), the rapid distortion of vortices that occurs near the reattachment point and the ensuing propagation after passing through the trailing edge produce large fluctuations in velocity, thus being important sources of noise. In addition, low frequency noise can also be produced, since the position of the vortex inside the cove is non-stationary (CHOUDHARI; KHORRAMI, 2006; DOBRZYNSKI, 2010). It is believed that these mechanisms are responsible for the generation of the low frequency broadband component, typical of slat noise.

According to Yokokawa et al. (2008), the slat generates greater noise under conditions in which it does not sufficiently fulfill its aerodynamic role. The pressure fluctuations on the slat cove surface and consequently the noise produced decrease with increasing angle of attack. With increase of the angle of attack, the speed is increased through the slot, reducing the shear length (IMAMURA et al., 2009). According to Dobrzynski and Pott-Pollenske (2001), the shear layer extension directly impacts the noise level, since in a larger shear layer there is more time for the instabilities contained therein to amplify along its path towards the slat trailing edge. Depending on the pressure gradient in the region near the slot, the shear layer that emerges from the slat cusp is directed to the main element instead of moving toward the slat cove Yokokawa et al. (2008). In this situation, the disturbed portion of the flow may not reattach on the pressure side of the slat, passing through the slot, generating noise due to interaction between edges and turbulent flow (YOKOKAWA et al., 2008). In addition, with an increase in the angle of attack, the flow in the cove becomes less turbulent (TAKEDA; ZHANG; NELSON, 2002).

This mechanism together with the vortex shedding at the trailing edge are regarded as the main sources of slat noise. The vortex shedding at the slat trailing edge is responsible for the high-frequency tonal components of the sound spectrum (TAKEDA et al., 2001; KHORRAMI, 2003; HUANG; LI; WANG, 2013). This phenomenon is directly related to the geometric discontinuity that occurs at the trailing edge (BROUWER; RIENSTRA, 2008), since its thickness is finite (CHOUDHARI; KHORRAMI, 2006), and is also disturbed by the vortices that are ejected from the slat cove and pushed through the gap, which end up mixing with the slat wake (PASCHAL; JENKINS; YAO, 2000; KHORRAMI, 2003). Thus, the vortex shedding mechanism is not observed in real-scale and under flight conditions, since the relative thickness of the trailing edge is much lower under these conditions than in wind tunnel testing of small-scale models (CHOUDHARI; KHORRAMI, 2006; DOBRZYNSKI, 2010). Other model effects also occur due to low Reynolds of wind tunnel testing: low frequency tonal noise due to coherent laminar separation in the slat hook and high frequency tonal noise due to Tollmien-Schlichting instabilities in the boundary layer in the slat suction side, effects that can be eliminated through boundary layer tripping (DOBRZYNSKI et al., 1998). According to Huang et al. (2008), the vortex shedding on the cusp can also produce low frequency tones.

Knowing the main features of the flow in the slat region and its probable relations with the sound emissions, it is possible to design solutions for mitigate the noise generated by this source. Brouwer and Rienstra (2008) reports several projects in Europe aimed at solving the problem of aeronautical noise, acting on several fronts. Among the projects mentioned, there are researches at the University of Southampton that used plasma actuators to reduce aerodynamic noise. Dobrzynski (2010) and Yong, Xunnian and Dejiu (2013) also list several airframe noise reduction devices that have been studied under these projects.

According to Dobrzynski (2010) these devices should, firstly, not degrade the aerodynamic characteristics of the high-lift devices, maintaining the maximum lift and providing sufficient lift at moderate angles of attack. It should be considered that a loss of aerodynamic performance caused by a noise reduction solution should be compensated, for example, by an increase in speed, which in turn leads to an increase in the noise generated, compromising the reduction achieved by the solution that caused the degradation of aerodynamic performance (DOBRZYNSKI, 2010). Therefore, the most difficult requirement in the development of quiet high-lift devices is to maintain aerodynamic performance whereas noise generation is suppressed (YOKOKAWA et al., 2008). According to Huang, Li and Wang (2013), the key strategies to reduce slat noise are: relief or impedance of the shear layer impact on the pressure side of the slat; thickening of the shear layer to disrupt instabilities; break up of spanwise coherence or facilitation of three-dimensionality; enhancement of the shear-layer receptivity to the acoustic disturbances; reduction of the streamwise flow speed by oblique shocks. Choudhari and Khorrami (2007) also suggests that an optimal strategy to mitigate broadband slat noise should target the shear layer reattachment region, in order to reduce the amplitude of surface pressure fluctuations. Pereira et al. (2018) determined the location of the shear layer reattachment point in the slat cove through the coherence between two consecutive hot film sensors, finding that the reattachment position moves slowly toward the slat trailing edge with increasing angle of attack. The model in which Pereira et al. (2018) performed their measurements is the same one that will be used in the experiments of the research presented here. Thus, the results presented by Pereira et al. (2018) were directly used in the research presented at this dissertation, indicating the position in which the DBD-PAs was to be installed, following the suggestion of Chen (2012).

Some of the solutions that are currently under study are: application of acoustic liner on the surfaces of the slat cove and leading edge of the main element (MA; ZHANG, 2009); injection of air at the cusp to thicken the shear layer, making it less sensitive to disturbances and thereby moving the reattachment point closer to the trailing edge (HUANG; LI; WANG, 2013); increasing the extension of the seal, which reduces the intensity of the vortices that develop in the shear layer, thereby reducing the length of the shear layer and shifting the reattachment closer to the trailing edge (CHOUDHARI; KHORRAMI, 2006); filling of the cove with slat cove fillers, which have a specific geometry that guides the flow along a desired path (without degradation of aerodynamics) and reduce flow instabilities (IMAMURA et al., 2007; TURNER et al., 2013); application of perforated materials, brushes, foams and serrated tapes at the trailing edge (MA; ZHANG, 2009). In the case of cove fillers, Dobrzynski (2010) highlights the disadvantages of being optimized for just one angle of attack and hampering slat retraction. Dobrzynski (2010) also mentions the possibility of aerodynamic degradation with the application of perforated materials at the trailing edge.

Although there are so many solutions in the literature, Yong, Xunnian and Dejiu (2013) notes that the developments in airframe noise reduction solutions adopted by the industry have reached an asymptotic level of improvement in recent years and that this trend indicates that the ACARE noise reduction goal will not be reached by 2020. In this way, Yong, Xunnian and Dejiu (2013) believes that alternative solutions should be sought, more specifically, active flow control (plasma, air blowing, suction). The researches in active control applied to noise reduction of airframe, however, are still in a primitive stage (YONG; XUNNIAN; DEJIU, 2013), requiring more researchers to look into this question.

Besides the preservation of the aerodynamic performance, Dobrzynski (2010) also points out that the following constraints must be observed in the design of an airframe noise reduction device: reliability (malfunctioning of the acoustic treatment should not affect the aircraft performance), handling quality (there should be no sudden changes in forces and moments with the activation of noise reduction devices), weight, structural constraints, system complexity and maintainability. As will be shown in the subsection 2.2.7, plasma actuators are active flow control devices that fulfil many of these constraints and are therefore a potential solution.

In the opinion of Yong, Xunnian and Dejiu (2013), the effectiveness of the use of plasma in the noise reduction of high-lift devices has not yet been published, although several concepts have already been considered by research groups such as the University of Notre Dame and the University of Southampton. Yong, Xunnian and Dejiu (2013) suggests that plasma actuators applied to the surface of the slat cove and leading edge of the main element could function as a virtual acoustic liner, whereas plasma actuators placed chordwise at the slat trailing edge would produce streamwise vorticity, acting as a virtual serrated trailing edge (Figure 7). Besides, according to them, the plasma applied to the slat hook could reduce instabilities in the shear layer. These techniques that use plasma actuators, however, need to increase their control authority, since they lose their effectiveness with the increase of the speed of the freestream, being not practical yet for the Reynolds values and speeds found in flight by a real aircraft (YONG; XUNNIAN; DEJIU, 2013).

Figure 7: (a) Plasma acoustic liner; (b) Plasma virtual serrated edge.

Source: Yong, Xunnian and Dejiu (2013)

2.2 Plasma actuators: characteristics and operating principles

Being the solution proposed in this research to airframe noise problem, an overview of the theory behind the plasma actuators is provided in this section. The understanding of the physical mechanisms behind the dielectric barrier discharge and the knowledge of how geometry, materials and operating parameters affect the DBD-PA performance are essential to the experiments developed next. A brief discussion on the advantages and disadvantages of using plasma actuators is also presented.

2.2.1 Dielectric barrier discharge plasma actuators (DBD-PAs)

The electrohydrodynamic (EHD) control is a form of active flow control obtained from the interaction between a partially ionized airflow and an intense electric field, resulting in a Lorentz collision force in the neutral gas (ROTH; SHERMAN; WILKINSON, 2000). In atmospheric conditions encountered in commercial aircraft flight, the low air temperature does not provide sufficient ionization due to Saha equilibrium, and a source of charged particles is required to control the flow through EHD phenomena (ROTH; SHERMAN; WILKINSON, 2000). A possible source of these particles is the generation of a weak plasma directly into the flow through dielectric barrier discharge actuators (ROTH; SHERMAN; WILKINSON, 2000).

Plasma is a quasi-neutral particle system in the gaseous form consisting of a mixture of free electrons, ions and neutral particles (HIPPLER, 2001). Such electrical particles result from the dissociation of the molecules of the gas when sufficient energy is added to it, causing the kinetic energy of the particles to exceed the intermolecular bonding energy (ROTH; SHERMAN; WILKINSON, 2000). The collective behavior of these particles is characterized by long-range Coulomb interactions in which the collision between electrons and neutral particles occurs at a frequency of the same or greater order than the plasma driving frequency (CORKE; POST; ORLOV, 2007). Plasma can be thermal or nonthermal (cold), depending on the relative temperature between electrons and ions. A thermal plasma is characterized by the high temperature of both ions and electrons, which are in thermal

equilibrium. The low temperature nonthermal plasma is characterized by the high kinetic energy of only the electrons in relation to the average kinetic energy of the other particles of the fluid, the fluid remaining at ambient temperature (ROTH; SHERMAN; WILKINSON, 2000; CORKE; POST; ORLOV, 2007). The nonthermal atmospheric plasmas can be produced through different regimes of electric discharge, at a low energy cost, since most of the electrical energy supplied is used in the production of energetic electrons and ion acceleration, not in the heating of the surrounding air (ROTH; SHERMAN; WILKINSON, 2000; MOREAU, 2007). The discharge regime is determined by the voltage-current curve, and can be a dark discharge, corona discharge, glow discharge (dielectric barrier discharge) or arc discharge (MOREAU, 2007; CROCE, 2014). For further information on the various discharge regimes, see Moreau (2007) and Croce (2014).

Initially the atmospheric cold plasma generation devices were designed for industrial applications of ozone generation and pollutant removal (MOREAU, 2007). The first aerodynamic application of dielectric barrier discharge was published by Roth, Sherman and Wilkinson (1998), which patented a device called OUAGDP (One Atmosphere Uniform Glow Discharge Plasmas). According to Roth, Sherman and Wilkinson (1998) the DBD is the most easily scalable type of discharge to operate under high Reynolds conditions, closer to real aeronautical applications, in relation to other discharge regimes (corona, for example). In addition, DBD is more stable and less sensitive to air humidity than other discharge regimes (TOUCHARD, 2008). Thus, although there are plasma actuators based on other discharge regimes, DBD-based devices are the most used in the recent researches (MOREAU, 2007). For information on plasma actuators based on other discharge regimes, see Touchard (2008).

DBD plasma actuators are completely electric devices, without of pneumatic, hydraulic and moving parts, which directly convert electric energy into kinetic energy, inducing an airflow called ionic wind (MOREAU, 2007; WANG et al., 2013). They are lightweight, very thin and fast-reacting, being ideal for aerodynamic control (WANG et al., 2013). In general, they are composed of two flat electrodes mounted on opposite sides of a dielectric (Figure 8), which are subjected to a high AC voltage (usually from a few kV to 30 kV , with frequencies from 100 Hz to a few tens of kHz) (MOREAU, 2007; WANG et al., 2013). When this AC voltage is high enough, the intense electric field produced ionizes the air above the covered electrode, forming an atmospheric cold plasma (CORKE; POST; ORLOV, 2007). This ionization occurs through a Townsend electron avalanche mechanism, where the primary electrons multiply in an ionization cascade (MOREAU, 2007): the electrons released by the cathode are accelerated in the electric field towards the anode, colliding in the path with neutral molecules that are then ionized, releasing more electrons that are also accelerated towards the anode by the strong electric field. This ionized air, in the presence of the electric field (whose direction is defined by the geometry of the actuator), results in a body force acting to accelerate the air (CORKE; POST;

ORLOV, 2007). The asymmetric configuration of the DBD-PA creates a suction region on the exposed electrode causing air in the vicinity of the device to be drawn toward the wall, from where it is then ejected tangentially to the surface from the exposed electrode edge, over the region of the encapsulated electrode, thereby inducing a pseudo wall jet (ENLOE et al., 2006; LITTLE et al., 2009; ZHANG et al., 2017). This DBD induced jet differs from the classic wall jet because in the case of DBD, mass is not injected into the flow, only momentum (WANG et al., 2013; ZHANG et al., 2017).

Figure 8: Schematic cross section of a dielectric barrier discharge plasma actuator (out of scale)

Source: The author

In the DBD regime, the dielectric barrier in the discharge region prevents spark formation (typical problem of corona discharge actuators, which causes instabilities and electrode damage) (MOREAU, 2007). In this way, DBD is able to produce and sustain a large volume of discharge at atmospheric pressure without collapsing in an arc, being a more stable discharge regime, and therefore capable of inducing a more intense blow (CORKE; POST; ORLOV, 2007; MOREAU, 2007). In addition, to avoid plasma formation on both sides of the actuator, which would reduce its efficiency, the grounded electrode must be completely encapsulated in the dielectric (MOREAU, 2007). The encapsulation of this electrode also allows the generation of a more stable and diffuse plasma discharge (CORKE; POST; ORLOV, 2007).

The fact that the ionic wind produced is unidirectional and dependent on the orientation of the asymmetric electrodes implies that there is some asymmetry between the halves of the voltage cycle when operating the actuator (ENLOE; MCHARG; MCLAUGHLIN, 2008). Despite the uniformity of the plasma diffuse glow observed with the naked eye, through high-speed photographs it is possible to observe that the DBD is composed of a series of microdischarges that occur and extinguish very quickly in a sequential way, and that differ during the positive and negative half-cycles (MOREAU, 2007; ENLOE; MCHARG; MCLAUGHLIN, 2008). Enloe, McHarg and McLaughlin (2008) demonstrated that about 97% of the momentum coupling occurs during the negative portion of the discharge cycle and related this behavior to the large differences in the spatial and temporal

discharge structures between the positive and negative portions of the voltage wave applied to the electrodes.

Figure 9: (a) Negative going portion of cycle (forward stroke); (b) Positive going portion of cycle (backward stroke)

Source: Enloe et al. (2004)

In the portion of the cycle (Figure 9 a) where the exposed electrode is negatively charged (forward stroke), electrons are emitted by the exposed electrode and accumulate on the dielectric surface, over the region of the encapsulated electrode (MOREAU, 2007; ENLOE; MCHARG; MCLAUGHLIN, 2008). The accumulation of charges on the dielectric surface is a self-limiting phenomenon that inhibits the accumulation of more charges, opposing to the applied voltage and causing the plasma to be reduced until the discharge is interrupted (MOREAU, 2007; ENLOE; MCHARG; MCLAUGHLIN, 2008). In order to maintain the discharge it is necessary that the applied voltage be continuously varied, since the discharge is extinguished when the rate of change of the applied voltage decreases below a threshold (ENLOE; MCHARG; MCLAUGHLIN, 2008). Hence the need to operate with AC voltage (CORKE; POST; ORLOV, 2007; MOREAU, 2007; WANG et al., 2013). In addition, at atmospheric pressure, the breakdown voltage is lower for an AC input, since after the discharge has started, the electric field needed to maintain it is less than that necessary to trigger it (CORKE; POST; ORLOV, 2007). When the exposed electrode becomes more positive than the charged dielectric surface (backward stroke, Figure 9 b), the accumulated electrons return from the dielectric surface to the exposed electrode (ROTH; SHERMAN; WILKINSON, 2000; ENLOE; MCHARG; MCLAUGHLIN, 2008). Since the encapsulated electrode is not capable of emitting additional electrons, part of the electrons accumulated in the dielectric recombine with the ions produced in the previous half of the cycle when returning to the exposed electrode (ROTH; SHERMAN; WILKINSON, 2000). Therefore, when the exposed electrode is negatively charged, the plasma discharge is diffuse and homogeneous, interacting with a larger mass of air; when positively charged, the plasma discharge is filamentary, interacting with a smaller amount of air (MOREAU, 2007; ENLOE; MCHARG; MCLAUGHLIN, 2008). In addition to this difference in the air mass subject to plasma interference due to different discharge morphologies, there

is also a difference in the electric field structure caused by the geometric asymmetry of the actuator, which contributes to the unidirectionality of the blow (ENLOE; MCHARG; MCLAUGHLIN, 2008). In this way, the negative half-cycles induce a higher horizontal velocity than the positive half-cycles (MOREAU, 2007), causing the induced wind to be unidirectional despite the AC voltage applied.

Although there is heating of the electrodes and surface discharges modify the air properties in their proximity (density and viscosity), these effects may be neglected in comparison to those produced by electrohydrodynamic phenomena caused by the plasma actuator (ROTH; SHERMAN; WILKINSON, 1998; ROTH; SHERMAN; WILKINSON, 2000; MOREAU, 2007). In addition, the capacitive nature of the DBD-PA causes the electric current through the plasma to be mostly a displacement current (caused by the temporal variation of the electric field), and to a lesser extent a conduction current (caused by the displacement of ions and electrons), so that problems of overheating and corrosion are prevented (ROTH; SHERMAN; WILKINSON, 2000; PONS; MOREAU; TOUCHARD, 2005; MOREAU, 2007).

According to Abe et al. (2008), despite all the efforts presented in the literature, the mechanism of momentum transfer between the DBD and the adjacent air is not yet fully understood. According to Moreau (2007), momentum is inserted into the flow in the exposed electrode region, and the maximum velocity always occurs at the end of the plasma region, over the encapsulated electrode. The flow downstream this region is due only to diffusion of the momentum inserted in the plasma region (PONS; MOREAU; TOUCHARD, 2005). The most accepted mechanism is based on the collision of the ions accelerated by the electric field with the neutral molecules of the surrounding air (ROTH; SHERMAN; WILKINSON, 2000; MOREAU, 2007; ENLOE; MCHARG; MCLAUGHLIN, 2008; WANG et al., 2013). Although the electrons have speeds much larger than the ions, their mass is much smaller, making the transfer of momentum in the collisions very small, so the ions are the most responsible for the transfer of momentum, since they are heavier (ROTH; SHERMAN; WILKINSON, 2000).

So, in order to maximize the transfer of momentum between the plasma and the neutral gas, one must (ROTH; DAI, 2006): arrange the electric field lines and the electric field gradients in order to accelerate the ions to the highest possible speed, and increase the numerical density of the ions through a more efficient ionization. According to Roth and Dai (2006), this can be done by changing the properties of the dielectric, the characteristics of the input voltage and the geometric parameters of the actuator.

Since the operating conditions (applied electric field, cross-sectional area of the electrodes and static air pressure) define the current density in the plasma region, defining the discharge regime (CORKE; POST; ORLOV, 2007), the electrical and mechanical characteristics of the plasma formed by DBD depends heavily on several parameters,

such as width of each electrode, gap between electrodes, dielectric thickness and material, applied voltage, AC frequency, waveform, duty cycle and modulation frequency (MOREAU, 2007). The influence of these parameters is presented in the following sections.

2.2.2 Influence of geometry and materials

The electrical and mechanical characteristics of the produced plasma depend strongly on several parameters, such as electrode dimensions, gap, thickness and dielectric material (MOREAU, 2007). The dissipated power does not depend on the geometry of the electrode, however the force produced in the flow is strongly dependent on this geometry (ENLOE et al., 2004).

The plasma forming region is limited by the width of the encapsulated electrode (or by its extension in the direction of the induced flow), since the electric field is established between the electrodes, not exceeding them (ENLOE et al., 2006; MOREAU, 2007). Therefore, since the production and acceleration of ions and the momentum exchange occurs in the plasma region, the larger the encapsulated electrode is, the greater the maximum velocity induced by the actuator (ENLOE et al., 2004; CORKE; POST; ORLOV, 2007; MOREAU, 2007). However, since the phenomenon that supports plasma is dissipative, the researches show that this relationship is asymptotic (Figure 10), so that the plasma produced by a DBD is not able to expand by more than about 20 mm (FORTE et al., 2007; MOREAU, 2007). The width of the encapsulated electrode defines the saturation voltage, from which it is no longer possible to increase the intensity of the blow produced (CORKE; POST; ORLOV, 2007). Although the width of the encapsulated electrode significantly influences the induced velocity, it practically does not affect the power consumed per unit length (ROTH; DAI, 2006).

Figure 10: Asymptotic behavior of the maximum induced velocity with the encapsulated (grounded) electrode width

Source: Forte et al. (2007)

The exposed electrode width does not interfere with actuator performance, however its thickness is important, more particularly the sharpness of its edge near the encapsulated electrode (ENLOE et al., 2004; CORKE; POST; ORLOV, 2007). The thinner the exposed electrode, the higher the momentum transfer to the air (ENLOE et al., 2004). The edge shape is also important (Figure 11). Abe et al. (2008) obtained a force 50% greater with an exposed electrode composed of a thin stainless steel mesh compared to a traditional metallic tape electrode of the same thickness. The result obtained by Abe et al. (2008) is due to the greater electric field concentration at the pointy ends of the mesh.

Figure 11: Influence of the exposed electrode edge in the momentum transfer

Source: Enloe et al. (2004)

A thicker dielectric can withstand higher voltages, allowing the production of higher net force, since a more intense and more parallel electric field can be generated without breaking the dielectric (ENLOE et al., 2004; MOREAU, 2007; HUANG et al., 2008; THOMAS et al., 2009). However, for a same voltage, a thicker dielectric reduces the efficiency of the actuator (ENLOE et al., 2004). A thinner dielectric, in turn, produces a higher velocity at a lower voltage, since the electric field generated is stronger (FORTE et al., 2007), however it is more susceptible to instabilities in the discharge, increasing the occurrence of damages by electric arcs (Figure 12). In this way, a parameter more relevant than the thickness itself is the bulk capacitance of the actuator. The higher the bulk capacitance the better the performance of DBD-PA (LITTLE et al., 2009; THOMAS et al., 2009). For this, the ideal dielectric layer is one that possesses the largest dielectric constant and the smallest thickness (LITTLE et al., 2009). However, there is a trade off here, because the thinner the dielectric layer, the lower is its capacity to withstand high voltages without forming arcs that damage the dielectric. Therefore, the choice of the dielectric material should also consider obtaining the maximum dielectric strength and the ability to avoid chemical degradation the presence of plasma (ROTH; DAI, 2006;

THOMAS et al., 2009). Roth and Dai (2006) lists several possible materials, highlighting the polyimide film (also known by its trade name, Kapton), which has a good dielectric strength, allowing the use of thinner layers of dielectric. Most of the works found in the literature make use of this material as dielectric, due to its good properties and ease of making the actuators with it, since it is sold in the form of self-adhesive tape. According to Patel et al. (2007a), the polyimide has a breakdown voltage of about 7 kV per 10^{-3} in of thickness and a dielectric constant of 3.3.

Figure 12: Influence of the dielectric thickness (a) in the maximum velocity

Source: Forte et al. (2007)

Although several researchers have used a zero gap, it is not clear that this design is optimal, since the most intense part of the electric field is concentrated in the dielectric material and not in the plasma generation region (ROTH; DAI, 2006). However, the gap length should not be too large, since the electric field and the electric field gradient decrease with this increase in distance between the electrodes, causing the actuator performance to drop drastically from a certain gap (ROTH; DAI, 2006; CORKE; POST; ORLOV, 2007). Before this threshold is reached, however, there is an increase in ionic wind strength with an increasing in the gap (Figure 13), due to the orientation of the electric field (FORTE et al., 2007). Therefore, there is an optimal gap value, which according to Roth and Dai (2006) is between 1 and 2 mm. Corke, Post and Orlov (2007) recommends, however, that for handmade electrodes a small overlap between the electrodes should be done, to avoid irregularities in the gap that could affect the uniformity of the flow.

Figure 13: Influence of the gap between electrodes in the maximum velocity

Source: Forte et al. (2007)

Some alternative configurations to that presented so far are also found in the literature, having their own peculiarities, advantages and disadvantages.

Aono et al. (2017) has developed micro DBD plasma actuators, which have electrodes with a width of less than 4 mm. The researchers analyzed the flow structures induced by different geometries of microactuators (straight and curved) and later tested the application to control the separation in an airfoil, obtaining better results with the curved microactuator, which produces three-dimensional flow structures. Through PIV, the authors observed that sinusoidal microactuators generate vortical structures and a suction effect that suppresses the flow separation at low angles of attack.

Asaumi et al. (2017) tested a tri-electrode configuration also applied to the separation control in an airfoil. In this configuration, an additional exposed electrode is added to the traditional DBD configuration, downstream of the encapsulated electrode (Figure 14). The upstream electrode is connected to a high AC voltage source while the downstream electrode is connected to a high DC voltage source, and the encapsulated electrode is grounded. In this configuration, a plasma sheet is generated to a greater extent in which a greater momentum transfer between plasma and air occurs (sliding discharge regime) (NISHIDA; NAKAI; MATSUNO, 2017). Asaumi et al. (2017) obtained better performance with the configuration in which the DC electrode was polarized from a certain negative voltage, which allowed the production of a ionic blow of higher intensity with little increase in the energy consumed (in relation to the traditional configuration of DBD). According to Asaumi et al. (2017), considering the generated thrust divided by the total power consumed, the tri-electrode configuration was 1.6 times more efficient than the single DBD-PA configuration. This is due to the fact that the negatively polarized DC electrode constitutes an extra source of electrons for the plasma (NISHIDA; NAKAI; MATSUNO,

2017). According to Nishida, Nakai and Matsuno (2017), depending on the operating conditions, the jet induced by the tri-electrode actuator can be deflected perpendicular to the dielectric due to the formation of two simultaneous opposing jets. This features could be useful to some applications.

Figure 14: Tri-electrode configuration producing a slide discharge regime

Source: Asaumi et al. (2017)

According to Thomas et al. (2009), Wang and Roy (2011), Croce (2014), Belan and Messanelli (2015) and Gao et al. (2017), compared to traditional straight electrodes of the same size, serrated electrodes produce a three-dimensional flow generating a thicker and more intense jet (Figure 15). Gao et al. (2017) performed a parametric study of plasma actuators with serrated electrodes, varying the parameters of tip sharpness and number of tips per unit length, verifying their influence on the maximum induced wind velocity, power consumption and average temperature. These phenomena are associated with the accumulation of electric charges that occur at the tips of sharp conductive objects. Since the plasma is formed at the edge of the exposed electrode, when it has a serrated geometry, there is a higher concentration of charges in the region where the plasma is generated in relation to the straight electrodes. (CROCE, 2014; GAO et al., 2017). According to Thomas et al. (2009), due to this higher electric field strength at the serrated points, plasma ignition occurs earlier in these geometries, but the saturation voltage is not altered by the serrated edge.

Figure 15: Thrust per unit span for straight and serrated electrodes.

Source: Thomas et al. (2009)

Gao et al. (2017) concluded that from a certain value of tip sharpness, the power consumed increases rapidly with the decrease of tip sharpness due to the intense electric field formed at the sharpest points, but the speed reaches a peak as the tip sharpness decreases, to a certain extent, and then the velocities decrease with more diminution of tip sharpness. This is due to the fact that the jet generated by the actuator is always perpendicular to the edge of the electrode, and from a certain tip sharpness, the edges tend to become more and more parallel to the flow, causing the jet component in this direction to be reduced, even though greater power is being dissipated by the actuator. In addition, Gao et al. (2017) observed that power consumption also increases rapidly with a decrease in the number of tips per unit length, from a certain value of this tip density. The smaller the tip density, the wider the area of gap between the electrodes, and the greater the impedance, which leads to the ionization of more particles and consequently to a higher power consumption. To some extent, the reduction in the number of tips per unit length leads to an induced speed increase, until it reaches a peak. After this value, an additional reduction of the number of tips leads to a reduction of the induced velocity, because with the increase of the gap, more energy is absorbed by the increase of the impedance and less by the momentum transform (GAO et al., 2017).

A slightly different form of two-dimensional actuators was proposed by Wang and Roy (2011). In the concept of Wang and Roy (2011), both electrodes, not just the exposed one, are two-dimensional, so that the blow is induced with equal intensity in the directions perpendicular to the edges (Figure 16). The researchers obtained a more intense wall jet with triangular, serpentine and square configurations in relation to the traditional linear configuration of DBD-PAs. The square actuator proved to be the most efficient for mixing.

These unconventional forms differ from the traditional ones by the three-dimensional effects they produce in the flow Wang and Roy (2011).

Figure 16: DBD-PA shapes proposed by Wang and Roy (2011)

Source: Wang and Roy (2011)

It is also possible to combine several plasma actuators in cascade to obtain a higher overall jet intensity. According to Enloe et al. (2004), the effect of multiple actuators is additive when positioned relatively close. This additive effect, however, is not linear with the number of actuators combined (THOMAS et al., 2009).

2.2.3 Influence of voltage and AC frequency

The main operational parameters that influence the performance of the DBD-PAs are the applied voltage, the AC frequency, the applied voltage waveform and if the operation is done in steady (duty cycle 100%) or unsteady mode, where the modulation frequency and the duty cycle are important.

The induced blow velocity increases with the voltage and AC frequency applied (PONS; MOREAU; TOUCHARD, 2005; MOREAU, 2007). This increase in velocity, however, does not occur unlimitedly with the increase in voltage. By keeping fixed the voltage and increasing the frequency or keeping fixed the frequency and increasing the voltage, the induced jet velocity increases until it reaches an optimal value, after which the performance is saturated or degraded (Figure 17), depending on the constitutive characteristics of the DBD-PA (ROTH; DAI, 2006). This value of the maximum speed reached by the blow increases asymptotically with the voltage and AC frequency applied (MOREAU, 2007). This occurs because the momentum transfer that induces the blow occurs in the plasma forming region, and the extent of the plasma-covered region is proportional to the applied voltage intensity and limited by the extension of the grounded electrode (CORKE; POST; ORLOV, 2007). This proportionality is related to the increase of the electric field intensity, responsible for the ionization of the air and the acceleration of the ions (FORTE et al., 2007). The increase in voltage or AC frequency applied to the electrodes leads to an increase in the average charge transferred per unit of time

(MOREAU, 2007). If these parameters are excessively increased, the accumulated charge becomes so high that the discharge becomes unstable, causing the occurrence of streamers or arcs through the dielectric, damaging it (MOREAU, 2007). Delaying the formation of these streamers is one way to gain greater control authority in the DBD-PAs (THOMAS et al., 2009). This can be done by changing the properties of the dielectric layer.

Figure 17: Asymptotic behavior of the maximum induced velocity with voltage and AC frequency

Source: Forte et al. (2007)

The frequency of applied voltage does not change the extent of the plasma-covered region, but for the same distance to be covered in the shortest time between cycle changes, increasing frequency leads to an induced increase in velocity (ENLOE et al., 2004; CORKE; POST; ORLOV, 2007). In addition, an increase in frequency increases the frequency of collision between ions and neutral molecules, favoring the exchange of momentum between plasma and neutral air (FORTE et al., 2007; CORKE; POST; ORLOV, 2007). For a given actuator a higher saturation force is obtained by reducing the applied AC frequency. However, when the actuator operates at a voltage below the saturation, an increase in the AC frequency leads to an increase in the intensity of the ionic wind produced (THOMAS et al., 2009). In this way, there is an optimal AC frequency for a given actuator, below which the produced body forces are weaker, and above which more electrode heating is produced than an increase in induced velocity (CORKE; POST; ORLOV, 2007). This optimum frequency depends on the static gas pressure and the capacitance of the actuator, which is proportional to the ratio ε/h (CORKE; POST; ORLOV, 2007), where ε is the dielectric constant and h is the dielectric thickness. In the case of Kapton (polyimide film), $\varepsilon = 3.3$ and the thickness is in the order of 0.15 mm , the optimum frequency is around 5 kHz for one Kapton layer (CORKE; POST; ORLOV, 2008).

Although from the point of view of mechanical efficiency (efficiency in converting

electric energy into kinetic energy of the flow), it seems beneficial to operate the actuator at higher voltages and higher frequencies, however it reduces the life of the device (GIEPMAN; KOTSONIS, 2011). In the glow discharge regime the current density in the plasma is independent of the current flowing through the circuit, but if this current density is increased until reaching the glow-to-arc transition threshold, instabilities arise and lead to the occurrence of electric arcs, which do not produce wind and damage the actuator (CORKE; POST; ORLOV, 2007).

2.2.4 Influence of waveform, unsteady and steady actuation

Several applications listed in the section section 2.3 make use of unsteady actuation (Figure 18), achieving better energetic efficiency and, in some cases, better performance. Energy efficiency is achieved due to the reduction in the total power dissipated, since the actuator is not continuously activated. In addition, a starting vortex is produced each time the actuator is activated (WANG et al., 2013), causing disturbances that may be useful in the boundary layer transition or in the disruption of acoustic feedbacks, also promoting a greater momentum transfer from the freestream to the boundary layer (LITTLE et al., 2009; BORGHI et al., 2017). According to Benard, Jolibois and Moreau (2009), these results suggest that in the case of separation control, the ionic blow velocity induced by the plasma actuator is not necessarily the primary control parameter, but rather the periodic perturbation in the boundary layer that promotes an interaction between vortices. Asada et al. (2009), Benard, Jolibois and Moreau (2009), Little et al. (2009) and Borghi et al. (2017), for example, obtained a higher separation control effect with a lower power consumption by operating the DBD-PA in unsteady mode. The work of Benard, Jolibois and Moreau (2009) suggests that the performance of the DBD-PA is optimal when the frequency of unsteady modulation coincides with the frequency of the vortex shedding of the aerodynamic body whose separation is being controlled. A similar result was obtained by Thomas, Kozlov and Corke (2008), who obtained better performance of his DBD-PA in reducing the oscillations within the wake of a cylinder when operating the DBD-PA at an unsteady frequency corresponding to unitary Strouhal (where the cylinder diameter is the reference length, and the velocity of the freestream is the reference velocity). This unitary Strouhal based on the unsteady frequency was also proved to be more efficient by Corke, Mertz and Patel (2006), who used a DBD-PA to delay separation in an airfoil.

Figure 18: Unsteady actuation and duty cycle definition

Source: Corke and Post (2005)

In addition to using a duty cycle smaller than 100%, the applied voltage waveform also interferes with actuator performance. As mentioned in subsection 2.2.1, the difference in plasma emission in the halves of the voltage cycle is due to the different electron sources in each half of the cycle: in the negative-going half cycle the electrons are supplied by the exposed electrode (ideally an infinite source of electrons that offers them readily); in the positive-going half cycle the electron source is the surface of the dielectric, charged electrically in the earlier half of the cycle (a limited source of electrons and not readily available) (CORKE; POST; ORLOV, 2007). This asymmetry in the transfer of momentum between the halves of the voltage cycle suggests that the intensity of the jet produced by the DBD-PA can be maximized by choosing an optimal waveform for the input voltage of the DBD-PA (KOTSONIS; GHAEMI, 2012). According to Corke, Post and Orlov (2007), considering that there is a phase of the cycle in which the electrons are removed from the dielectric, in which the produced plasma intensity is much smaller: square waves are the worst, sine waves are good and triangular waves (saw tooth) are even better. Kotsonis and Ghaemi (2012) tested a family of asymmetric waveforms constructed in combinations of sine and square waves. Through these experiments, Kotsonis and Ghaemi (2012) concluded that waveforms with abrupt voltage drop during the early stages of the forward stroke produce significantly less thrust, while waveforms with abrupt voltage increases at the beginning of the backward stroke generate more thrust.

2.2.5 Influence of atmospheric properties

In addition to the constructive and operational parameters, the oxygen fraction in the atmosphere also has a direct correlation with the DBD-PA efficiency (ENLOE et al., 2006), since oxygen strongly influences the momentum transfer characteristics of the actuator (ABE et al., 2008). According to Enloe et al. (2006), the reason for this is that although the DBD plasma is largely composed of heavy positive ions and light electrons, the oxygen present in the atmosphere allows the formation of a small but important population of negative ions due to the addition of electrons to oxygen. The higher the

oxygen concentration, the better the DBD-PA performance (Figure 19).

Figure 19: Oxygen concentration influence in the DBD-PA efficiency

Source: Enloe et al. (2006)

This dependence on the composition, however, is reduced at lower atmospheric pressures (ABE et al., 2008). This is because the force generated by the plasma actuator on the fluid is also influenced by the ambient gas pressure (ABE et al., 2008). According to Abe et al. (2008), the momentum transfer performance of the DBD-PA does not decrease monotonically with the reduction of the atmospheric pressure. There is an optimum pressure depending on the atmospheric composition and the plasma actuator configuration. Below and above this optimal pressure, the performance of the plasma actuator is degraded (Figure 20).

Figure 20: Pressure influence on the induced airflow velocity

Source: Abe et al. (2008)

2.2.6 Mathematical modelling and control systems

Although one of the advantages of plasma actuators for application in control systems is their fast response, the difficulty lies in their mathematical modeling. Considering the complexity of the flow dynamics of interest, the mathematical modeling of the fluid system is a critical problem in the closed-loop control applications (CHO; SHYY, 2011). According to Cho and Shyy (2011), the high dimensionality and nonlinearity inherent to most fluid dynamics problems are the causes of the main difficulties in modeling the dynamics of these systems and incorporating an effective control system. Roth, Sherman and Wilkinson (2000) emphasize that a detailed theoretical mathematical modeling of the phenomena involved in the operation of the DBD-PA requires a coupling of the Maxwell equations with the Navier-Stokes equations, including a chemical modeling of the plasma formation, being a very complex problem. Wang and Roy (2011) points out that although there are several different approaches in the literature to computationally model plasma actuators, there is still no definitive and complete model for the phenomena, which takes into account all physical parameters. Roth, Sherman and Wilkinson (2000) performed a mathematical modeling of the DBD-PA. The modeling presented by Roth, Sherman and Wilkinson (2000) is based on a phenomenological electromagnetic model in conjunction with the Navier-Stokes equations, with the para-electric force being modeled as a body force field in the plasma forming region. Corke, Post and Orlov (2007) also mentions several attempts to model DBD-PAs computationally, emphasizing that several of them can not predict all the physical phenomena involved in the DBD-PAs operation, while more complex formulations that include a chemical modeling of the air ionization coupled to the Navier-Stokes equations and Poisson equations have a very high computational cost. A very widespread model used in other works was proposed by Shyy, Jayaraman and Andersson (2002). However, as Moreau (2007) points out, the computational model of Shyy, Jayaraman and Andersson (2002) is based on incorrect hypotheses, producing results that do not correspond to those experimentally observed, being critical to use it in control systems.

In this way, empirical modeling is more feasible, although it is limited and requires experiments that characterize each configuration of DBD-PA. The system identification approach produces models based on a series of inputs and outputs. Although this form of modeling does not carry detailed information on flow dynamics, information of interest for control purposes is directly accessible (CHO; SHYY, 2011). In addition, if the key characteristics of the system dynamics are properly captured, this simplified modeling can reduce the susceptibility of the control system to uncertainties of the modeling, which will certainly be present in systems whose physics of the problem is very complex (CHO; SHYY, 2011). Finally, Cho and Shyy (2011) note that a control based on fixed gain usually requires knowledge of the system parameters and of the statistical properties of the signals

noise. More suitable, therefore, is the implementation of an adaptive control technique, which is able to dynamically update controller gains in response to plant changes or disturbances in the environment, being a good tool to control plants whose dynamics can not be directly modeled (CHO; SHYY, 2011). However, adaptive algorithms are efficient only when the number of undetermined parameters is relatively small so that the evaluation of the functions can be performed quickly.

2.2.7 Advantages and disadvantages

The several advantages of plasma actuators give this devices a great potential for applications. Although its drawbacks limit its applicability, they indicate exactly at which points a further development of the technology is needed, guiding the researchers of the area.

The main advantages of DBD-PAs are: simplicity; low power consumption consistent with embedded applications (in the order of $0.3kW/m^2$, according to Roth, Sherman and Wilkinson (2000)); fast response and real time control capability at high frequencies; direct conversion of electrical energy into kinetic energy of the flow without the use of moving, hydraulic or pneumatic parts; low weight; small thickness that can be integrated into an aerodynamic body without causing great perturbations to flow when deactivated (ROTH; SHERMAN; WILKINSON, 1998; MOREAU, 2007; WANG et al., 2013; ZHANG et al., 2017; JOSEPH et al., 2017). In relation to plasmas produced by other discharge regimes, the dielectric barrier discharge has the advantage of being more stable and capable of inducing a more intense blow (MOREAU, 2007).

Despite all these advantages over mechanical devices, the DBD-PAs effectiveness in flow control decreases with the increase in Mach number or in Reynolds number of the flow, because the momentum introduced by the plasma actuator becomes small in comparison to the momentum of the freestream, being an operational limitation (KOTSONIS; GHAEMI, 2012; ZHANG et al., 2017). Roth, Sherman and Wilkinson (2000) believe that this plasma actuator configuration is unlikely to allow an increase of one order of magnitude at the speeds usually produced, thus being a form of flow control effective only for low Reynolds conditions. This is due to the low energy conversion efficiency achieved by DBD-PA (MOREAU, 2007). According to Giepman and Kotsonis (2011), this low efficiency does not mean that the DBD-PAs are not effective as flow control devices, because mechanical efficiency should not be the only parameter analysed, since in the works found in the literature the plasma actuators were demonstrated to be excellent flow control devices in various applications, from significant reductions in drag to damping of oscillations in the flow, consuming a very low electrical power for this. In this way, Moreau (2007) notes that an improvement must be made to allow plasma actuators to operate at speeds compatible with those encountered in real flight, as well as large-scale models must be tested.

In addition, the DBD phenomenon is accompanied by high-intensity radiofrequency electromagnetic noise (THOMAS; KOZLOV; CORKE, 2008), which may be a problem in embedded applications if there is inadequate electromagnetic shielding or signal filtering in other devices and in the plasma actuator circuit itself. Thus, Houser (2013) recommend that an evaluation of electromagnetic field exposure should be carried out in DBD-PA applications, in order to avoid health harming and equipment damage (both in laboratory and in embedded applications). Moreau (2007) also mentions that the main disadvantage of DBD-PAs in relation to other types of plasma actuators is the occurrence of high peaks in the input power, although the average power consumed is quite low. This problem can be considerably reduced by using inductive filters between the power source and the actuator (MOREAU, 2007).

Finally, since tropospheric ozone is harmful to health, it is important to quantify its production in the proposed flow control applications of DBD-PA (HONG et al., 2014). According to Hong et al. (2014), the ammount of ozone produced is directly proportional to the power dissipated at the actuator. The researchers reported an ozone avarege production of $21g/kWh$. Hong et al. (2014) note that although this rate is much lower than that of an industrial ozonizer, it is still far from being negligible. According to the European directives (EUROPEAN UNION, 2002), the threshold alert for tropospheric ozone concentration is 180 micrograms of ozone per cubic meter of air, which is equivalent to $0.09ppmv$ at ambient pressure and temperature (HONG et al., 2014). Despite this, in all the works collected in this literature review, no author have mentioned the ozone produced by their plasma actuators during active flow control applications.

2.3 Applications of plasma actuators

Several applications for plasma actuators are proposed in the literature. In this section are highlighted applications related to active flow control to improve aerodynamic characteristics and applications related to the mitigation or attenuation of aerodynamic noise.

2.3.1 Aerodynamic improvements

Most applications found in the literature refer to aerodynamic improvements. These improvements are related to flow separation (Figure 21) and boundary layer transition control. These principles of operation allow a series of applications found in the literature, such as: roll and pitch control without the use of moving surfaces, generation of streamwise vortices, generation of wall jets without the need of a pneumatic source and increase of lift without the use of flaps and slats (WANG et al., 2013). Some of these works are listed below to exemplify the potential applications of plasma actuators, including less common electrode configurations and operational recommendations. A more extensive list

of applications can be found in some review articles, such as those published by Moreau (2007) and Wang et al. (2013). Caruana (2010) also lists a series of PA applications investigated in the context of the PLASMAERO project, a consortium of universities and European research institutes.

Figure 21: Reattachment of the flow in an airfoil when the DBD-PAs are activated

Source: Roth and Dai (2006)

Benard, Jolibois and Moreau (2009), for example, obtained a reduction of 37% in drag coefficient and stall delay (increase of maximum lift coefficient of up to 160%) in an airfoil equipped with plasma actuators at the leading edge. The researchers suggest that this configuration of plasma actuators could replace mechanical flaps and slats (which add significant weight to the aircraft and produce broadband noise). This suggestion, however, would hardly be certifiable. To achieve this result, Benard, Jolibois and Moreau (2009) operated their DBD-PA in unsteady mode (subsection 2.2.4).

Another proposal for replacing high-lift devices with DBD-PAs was made by Zhang et al. (2017), which experimentally tested two configurations of DBD-PAs, one asymmetrical (traditional) and one symmetric, applied to the leading edge of a wing for control of flow separation. According to Zhang et al. (2017), the replacement of classic high-lift devices (such as slat) by DBD-PAs would be a way to reduce carbon emissions and save energy, since DBD-PAs do not add significant weight and drag to the aircraft, unlike traditional slat mechanical devices. However, as previously mentioned, this replacement would be difficult to homologate due to safety issues. In their research, Zhang et al. (2017) concluded that the symmetrical configuration can delay the separation of the flow at speeds up to 100 m/s flow (Figure 22), having better performance than traditional asymmetric configuration. Through PIV measurements, the researchers were able to conclude that the vortices induced by the symmetric configuration are responsible for the better performance of this configuration. Such configuration continued to have control authority at high speeds, in which the asymmetric actuator had no more control authority. At the velocities where

both were able to control the flow, the symmetric actuator presented greater delay of the detachment and reduction of drag. Zhang et al. (2017) explain that in the case of the symmetric actuator, momentum is transferred from one side in the direction of flow and the other side in the direction opposite to the flow, causing them to entangle, forming a vortex. This vortex grows over time creating large-scale perturbations that promote momentum exchange between low speed and high speed regions. This causes the boundary layer to have more energy to overcome the adverse pressure gradient, preventing separation.

Figure 22: Stall delay produced by plasma slats

Source: Zhang et al. (2017)

Corke, Mertz and Patel (2006) also propose the use of plasma flaps to eliminate the complexity of moving parts, highlighting that the actuators should be optimized in conjunction with the geometry of a laminar airfoil. It is worth mentioning that in the work presented by Corke, Mertz and Patel (2006) the best efficiency of the unsteady actuation is produced when Strouhal equals one (considering the airfoil chord, freestream velocity and plasma modulation frequency), as mentioned in section subsection 2.2.4.

The stall delay application was also explored by Patel et al. (2007b). These researchers have developed an intelligent system that detects the imminence of stall and activates plasma actuators that act as slats without moving parts, turning them off when there is no need.

In all these applications, the main mechanism of separation control is not due to the addition of momentum to the flow by the DBD-PA, but to the momentum entrainment caused by the strong Reynolds stress, resulting from the interaction between the freestream and the jet induced by the plasma actuator (ASAUMI et al., 2017; ZHANG et al., 2017).

According to Wang et al. (2013), DBD-PAs can also be used as vortex generators to

“reenergize” the boundary layer, taking momentum from the freestream to the boundary layer. When tilted at some angle in relation to the direction of flow, the plasma actuators create streamwise vortices which promote a mixture between the boundary layer and the freestream (WANG et al., 2013). Mechanical vortex generators bring the penalty of increased pressure drag, while PA vortex generators have no associated pressure drag.

According to Porter et al. (2007), the greatest flow control potential of the DBD-PA is when it is acting as an electronic boundary layer trip, since the momentum addition itself is still quite small in relation to the freestream momentum in a typical aeronautical operation condition. The plasma actuator adds considerably less momentum than other techniques, like air blowing, for example. For real-scale applications, the addition of momentum becomes much less significant than in wind tunnel scales, so that the boundary layer transition caused by the actuator becomes a much more relevant feature.

Roth, Sherman and Wilkinson (1998) have demonstrated that DBD-PA are capable of generating electrohydrodynamic forces of sufficient magnitude to alter the near-wall turbulence and drag, showing that such devices can be used as active flow control mechanisms.

A slightly different configuration for lift recovery was implemented by Borghi et al. (2017). In their work, the researchers assembled a set of adjacent actuators along the surface of a NACA 0015 airfoil. Each one of these actuators produced a jet of opposite direction to its neighbouring actuators, such that the produced jets interact, making the resulting jet to have a component perpendicular to the PA. This allows the jets to be vectored when two adjacent actuators are subjected to different voltages. The best results obtained by Borghi et al. (2017) are also related to the unsteady actuation mode. Little et al. (2009) also obtained better performance through unsteady actuation, which proved to be more effective in reducing the flap separated region.

Still in the boundary layer control, Grundmann and Tropea (2009) used DBD-PAs mounted downstream to Tollmien-Schlichting waves in order to dampen these boundary layer oscillations. Steady and unsteady actuation were tested. According to Grundmann and Tropea (2009), the damping mechanism consists of two parts in the case of steady actuation: the body force created by the actuators accelerates the flow and modifies the velocity profile, making it more stable, causing the critical Reynolds to be greatly increased; and the reduction of the boundary layer thickness by the actuators leads to a smaller local Reynolds. In this way, the local Reynolds moves considerably away from the critical Reynolds, delaying the transition. In their experiments, Grundmann and Tropea (2009) used a system that adjusts the frequency and amplitude of the plasma actuator and the phase between the actuator signal and the waves, so that the plasma actuation cancels the Tollmien-Schlichting waves.

Some work on rotating elements has also been developed. According to Lombardi,

Bowles and Corke (2013), plasma actuators are ideal for flow control in helicopter rotors, as their lightweight structures and absence moving parts are suitable for operating under high G loads. In addition, the rapid response of these actuators can be synchronized with the high rotational speeds of the rotor. Lombardi, Bowles and Corke (2013) have implemented a closed loop control system in which the plasma actuator operates in the “sensor mode”, producing small periodic disturbances which, if detected by a downstream pressure sensor, indicates detachment and activates the control mode of the actuator, which then starts to operate at high power. While the pressure sensor does not detect small disturbances (amplified by the boundary layer when there is separation), the actuator continues to operate in the sensor mode. Joseph et al. (2017) used DBD-PAs to alleviate aerodynamic loading on wind turbine airfoils. Wind turbine blades are subject to significant fluctuations in aerodynamic loading due to the unstable and inhomogeneous nature of the atmospheric winds, which reduce the fatigue life of these blades. Thus, the goal of Joseph et al. (2017) was to implement a closed-loop control system using the DBD-PAs to maintain a constant lift force on blades subject to random winds. By the time this literature review was conducted, the researchers had only performed an open-loop control. Initially the researchers found a linear relationship between the voltage applied to the plasma actuator and the lift coefficient variation around an equilibrium point. The researchers intend in the future to find a better mathematical description of the model to implement a closed-loop control system. Joseph et al. (2017) used an experimental plant identification technique, in which the amplitude of the high voltage applied to the electrodes was the input and the pressure measurements on the surface of the airfoil was the output. The DBD-PA was installed on the trailing edge of the airfoil to allow circulation control.

Some researchers have proposed the use of DBD-PAs as attitude control devices, replacing traditional moving control surfaces. Ramakumar (2005) tested a configuration of plasma actuators mounted on the tip of a finite wing, one parallel to the flow and another perpendicular to it. According to the researchers, this configuration allows rolling maneuvers when a differential actuation is performed or a general improvement in the lift when the actuators are activated simultaneously. Patel et al. (2007a) implemented DBD-PAs as surrogates to moving control surfaces in a UAV, allowing it to expand its flight envelope, operating under conditions in which conventional flaps and ailerons are not effective (for exemple at high angles of attack). In their experiments, (PATEL et al., 2007a) used an unsteady actuation, with a sawtooth waveform. Laten (2017) used a canard configuration equipped with plasma actuators on the wings to replace the elevons, to control the aircraft’s pitch and roll maneuvers.

Another proposal of using DBD-PAs to achieve aerodynamic improvements was made by Feng, Shi and Liu (2017). The authors proposed a virtual Gurney flap using two plasma actuators facing each other at the trailing edge of an airfoil. According to Feng, Shi and Liu (2017), the advantages over the mechanical gurney are: it does not

add drag penalty in cruise as fixed gurney flap does, and it has no moving parts nor complex mechanical devices as would be required for retractable gurney flaps. The effect produced in the simulations made by Feng, Shi and Liu (2017) was similar to that of a physical gurney flap, providing an increase in lift without the drag increase penalty. Performance was better when only the downstream actuator was activated. However, as in other applications, the drawback arises from the low speed induced by the DBD, which limits the operational speed of the device.

Finally, Hasebe, Naka and Fukagata (2011) conducted a numerical and experimental investigation of the use of DBD-PAs in an attempt to reduce the wing-tip vortex. Although their configuration has reduced the vortex intensity in the numerical simulation, it has also reduced the L/D ratio, and the researchers could not reproduce experimentally the conditions of their simulation due to limitations of their equipment. This result, together with the concept presented by Yong, Xunnian and Dejiu (2013), served as inspiration for the configuration tested in the chapter 4, where plasma actuators were used in an attempt to reduce flap side edge noise by reducing the intensity of the flap tip vortices.

2.3.2 Noise reduction

The noise generated by the interaction of the airflow with the landing gear is one of the main sources of airframe noise during approach to landing, together with the high-lift devices (SMITH, 2009; ZAPOROZHETS; ATTENBOROUGH; TOKAREV, 2011). In order to reduce the noise associated with Von Kármán vortex shedding that occurs in cylindrical bodies subject to an airflow, such as the landing gear struts, Thomas, Kozlov and Corke (2008) tested in a wind tunnel a cylinder equipped with DBD-PAs. The configuration tested by these researchers was able to completely eliminate the occurrence of Von Kármán vortex shedding (Figure 23), reducing the turbulence levels in the wake, thus reducing the sound pressure levels associated with this shedding. This application, therefore, would be able to attenuate the emission of airframe noise associated to the landing gear. Thomas, Kozlov and Corke (2008) operated their DBD-PA device in a pulsed manner (unsteady actuation), obtaining better effect at an unsteady actuation frequency equivalent to unitary Strouhal (considering the flow velocity, the cylinder diameter and the unsteady modulation frequency). Although a pulsed actuation has been effective in suppressing the shedding with only 25% of the duty cycle (and therefore with just 25% of the power consumed in constant operation), this mode of operation produces a tone in the unsteady operating frequency. This way, Thomas, Kozlov and Corke (2008) concluded that a continuous performance is more recommended for noise control applications, although it is energetically more costly.

Figure 23: Near-wake PIV flow visualization with DBD-PAs off and on, respectively

Source: Thomas, Kozlov and Corke (2008)

Another aeroacoustic problem present in aircraft is the generation of noise in cavities such as the weapon bay in military aircraft and the landing gear bay when opened. Huang et al. (2008) used plasma actuators to reduce aeroacoustic noise generated by rectangular section cavities, achieving a complete attenuation of the tonal noise at the cavity's dominant frequency. In their work, Huang et al. (2008) implemented a PID controller to operate the DBD-PA. For the controller design, it was necessary to apply a technique of experimental identification of the system dynamics, since the analytical modelling this dynamics is quite complex, being a problem still open. According to Huang et al. (2008) passive noise control devices do not work well outside the conditions for which they were designed. Active devices like piezoelectric actuators, suction and blowing present great difficulties of installation and maintenance, while plasma actuators are simple and inexpensive to build and install. The principle of using plasma actuators as airframe noise control is to change the flow around an object through the interaction of the fluid with electric fields, in order to change the sound field without modifying the shape of the object (BROUWER; RIENSTRA, 2008; HUANG et al., 2008).

Figure 24: DBD-PA applied to a leading-edge slat reducing tonal noise

Source: Chen et al. (2013)

Chen (2012) and Chappell et al. (2012) used a DBD-PA applied on the cusp of a leading edge slat for attenuation of tonal noise (Figure 24). Using the DBD-PAs both in open loop and closed loop, they obtained the attenuation of five tonal peaks, with a reduction of 20 dB in the dominant peak. A proportional feedback LQG controller was implemented, allowing better performance in the noise attenuation with lower power consumption and greater thermal stability. For the controller design, the researchers performed an experimental identification of the system using an ARX algorithm (CHEN, 2012). In order to identify the dynamics of the system, Chen (2012) maintained as constants the angle of attack, the velocity, the voltage and the frequency applied to the plasma, taking as input the percentage of the duty cycle and as output the RMS signal of a microphone installed in the slat cove. This technique limits the optimal range of operation of the controller to a single condition, which would be impracticable in a commercial application. Thus, a suggestion to overcome this problem is the implementation of an adaptive controller, which could operate properly even with changes in flight conditions. Chen (2012) proposes in his doctoral thesis that the DBD-PA be installed in other regions of the slat, as in the surface of the cove, in order that the broadband noise can be attenuated. In the chapter 5 of the research presented at this dissertation, this suggestion was taken into account during the open loop control experiments carried out by the author.

3 DBD-PA CHARACTERIZATION: JET VELOCITY PROFILE MEASUREMENTS AND DEGRADATION

In order to characterize the velocity profiles of the jet induced by the DBD-PAs used in the next chapters, a series of pressure measurements in quiescent air within the jet boundary layer was carried out. These measurements were made with the DBD-PAs installed on the surface of a flat plate and the results are described and commented in this chapter. The glow discharge patterns are also analyzed and a brief discussion about degradation and manufacturing of the DBD-PAs are presented.

3.1 Experimental set-up and methodology

3.1.1 High-Frequency/High-Voltage AC Power Supply (HFHVPS)

A complete description and the electric diagram of the High-Frequency/High-Voltage AC Power Supply (HFHVPS) built by Croce (2017)¹ is provided at Appendix A and Appendix B. It is composed by a high frequency wave generator and a high voltage transformer, both supplied by a DC power supply. With a high voltage probe and an oscilloscope, the calibration curves showed at Figure 25 were obtained.

Figure 25: High-Frequency/High-Voltage Power AC Supply calibration curves

Source: The author

The HFHVPS behavior is practically linear with the DC voltage input for a given output frequency (the coefficient of determination varies from 0.9695 to 0.9996

¹ The HFHVPS was designed and built by Dr. J. A. G. Croce and lend to the author in 2017.

for the frequencies tested). The considerable difference of calibration between different output frequencies are related to the high voltage transformer efficiency, which varies with this frequency (the resonance frequency of the circuit is also affected by the DBD-PA capacitance). This is somehow inadequate for comparing the DBD-PA performance in relation to the driven voltage frequency, since its amplitude cannot be hold at the maximum for all the frequencies tested with the same voltage input. Ideally, the output voltage should be a parameter independent of the output frequency.

3.1.2 Dielectric barrier discharge plasma actuators

Three types of DBD-PAs were used within this research: straight edge (Figure 26 and Figure 27), square serrated edge (Figure 28 and Figure 29) and double-serpentine serrated edge (Figure 30 and Figure 31). The serrated electrodes were etched in copper self-adhesive tape with ferric chloride solution, the same process used for etching printed circuit boards. All these plasma actuators were made with 1 layer of polyimide self-adhesive tape as substrate and 3 layers of polyimide self-adhesive tape as dielectric barrier.

Figure 26: Straight electrode DBD-PA dimensions.

Source: The author

Figure 27: Straight electrode DBD-PA.

Source: The author

Figure 28: Square electrode DBD-PA dimensions.

Source: The author

Figure 29: Square electrode DBD-PA.

Source: The author

Figure 30: Double-serpentine electrode DBD-PA dimensions.

Source: The author

Figure 31: Double-serpentine electrode DBD-PA.

Source: The author

3.1.3 Pressure measurements

The DBD-PAs presented at subsection 3.1.2 were installed on the working surface (a flat plate) of a manual three-axis positioning system. The axes fine-thread screws have pitches of 0.8 mm , 1.0 mm and 0.8 mm for the axes x , y and z , respectively.

A flat tip Pitot tube was attached to the end of the positioning system and a buzzer was used to indicate when the probe tip touched the working surface (Figure 32). The Pitot tube tip is approximately an ellipsis with 0.8 mm high and 2 mm width.

Figure 32: Double-serrated DBD-PA at the working surface of the boundary layer Pitot positioning system

Source: The author

This Pitot tube was connected to the total pressure input of a Baratron type 77H-10 pressure head. The reference input of the pressure head was connected to 3 static pressure taps at the working surface, near the DBD-PA. The pressure head was connected to a Baratron 77M-XR-3 electronic precision pressure meter indicator.

Then, the Baratron system was connected to a National Instruments NI USB-6210 multifunction data acquisition module, optimized for superior accuracy and fast sampling

rates. The NI USB-6212 was connected to a computer and the storage and processing of the acquired data was made with a MATLAB code implemented by Pereira and Silva(2018)².

3.1.4 Experimental procedures

Due to hardware limitations imposed by the manual positioning system, all the three configurations were tested only at 5.0 *kHz*, 30 *V* input (20.0 *kV* output for this frequency) and 100% duty cycle. In the *x* direction, the probe position was fixed at 10 *mm* from the grounded electrode upstream edge (in the case of double-serpentine serrated electrode, the line connecting the semicircles centers).

For each DBD-PA (except the straight one) the velocity profile was measured at two positions: first at the peak of the exposed serrated electrode and then at its valley. In each of these spanwise positions, the Pitot probe was moved upwards from the working surface in steps of 0.2 *mm* (until the height of 5.4 *mm*) and then in steps of 1.0 *mm* (until the height of 10.4 *mm*). The pressure measurements at each one of these points was taken at an acquisition rate of 1000 *Hz* during 5 *s*, and a mean value was calculated for each point.

These tests are summarized at the Table 1.

Table 1: DBD-PAs velocity profiles test matrix

	Straight electrode	Square serrated electrode	Serpentine serrated electrode
V_{in}	30 V	30 V	30 V
f	5.0 kHz	5.0 kHz	5.0 kHz
D.C.	100%	100%	100%
x	10 mm	10 mm	10 mm
y	0 mm	0 and 3 mm	0 and 2.5 mm
z	0.4 to 5.4 mm (0.2 mm step)	0.4 to 5.4 mm (0.2 mm step)	0.4 to 5.4 mm (0.2 mm step)
	and	and	and
	5.4 to 10.4 mm (1.0 mm step)	5.4 to 10.4 mm (1.0 mm step)	5.4 to 10.4 mm (1.0 mm step)
Measurements	Dynamic pressure	Dynamic pressure	Dynamic pressure

Source: The author

Considering the air as an ideal gas, with data from analog barometer, thermometer, and higrometer, the mean air density of $\rho = 1.06 \text{ kg/m}^3$ was obtained and used to calculate the air velocity from the dynamic pressure at each point. Since the measurements were made too close to the wall and the jet velocities was so small that viscosity effects inside the Pitot tube become important, these factors were taken into account by correcting the processed data according to the literature (MERRIAM; SPAULDING, 1935; MACMILLAN, 1954; BARLOW et al., 1999).

When it was possible, data was fitted to an equation with the form $U(z) = az^be^{-cz}$,

² Acquisition code implemented by Lourenço Tércio Lima Pereira, shared personally with the author, who upgraded the code in order to apply near-wall and low-speed viscosity corrections to measured data.

where $U(z)$ is the jet velocity in the x direction in m/s , z is the vertical distance from the surface in mm , and a , b and c are real fitted constants. This equation is not related to any analytic theory, it is purely a fitting curve that satisfies the ideal boundary conditions of zero velocity at the wall surface and at infinity distance from the wall.

3.2 Results and discussion

3.2.1 Jet profiles and plasma discharge patterns

The experimental results are presented here with the corrections mentioned in subsection 3.1.4 and respective fitted curve.

It can be seen at Figure 33 that the measured data from the straight electrode DBD-PA are well fitted to the assumed curve (coefficient of determination of 0.969). A relative good fit ($R^2 = 0.939$) was also obtained for the peak of the square serrated electrode (Figure 34), which locally is like the straight electrode DBD-PA. The difference is that it produced a slightly more intense and wide jet than the straight configuration. This may be due to higher charge density at the teeth of the serrated electrode compared to the charge density of the straight electrode DBD-PA.

At the square serrated electrode valley the intensity of the jet is higher than at the previous results Figure 35, but the coefficient of determination is poorer ($R^2 = 0.871$), indicating that the profile at this region does not fit so well in the equation proposed. The higher intensity is probably due to vector sum of the diagonal jet produced by the corners of the teeth (where there is a higher charge concentration due the pointy corners), and the poor fitting to the curve was probably due to three-dimensional effects produced by the non-uniformity of the electrode geometry.

In the case of the double-serpentine electrode DBD-PA, it was not possible to fit the data to the idealized curve, as can be seen at Figure 36 and Figure 37. Due to the interlacing of the electrodes, highly three-dimensional flow structures must be produced by this DBD-PA geometry, creating uncommon jet profiles. Another hypothesis is that the measurements were taken within a mixing region (in a x position where the jet was not fully developed yet). As a suggestion for future work, when a better and automated positioning system is available, further measurements should be carried out varying the x positions. It would allow the development of an analytic solution for the DBD-PA jet profiles, which could be then compared to the classical wall jet profile for a similarity analysis.

Figure 33: Velocity profile of the jet induced by the straight electrode DBD-PA, $V = 20.0$ kV , $f = 5.0$ kHz .

Source: The author

Figure 34: Velocity profile of the jet induced by the square serrated electrode DBD-PA, at the peak of the exposed electrode, $V = 20.0 \text{ kV}$, $f = 5.0 \text{ kHz}$.

Source: The author

Figure 35: Velocity profile of the jet induced by the square serrated electrode DBD-PA, at the valley of the exposed electrode, $V = 20.0 \text{ kV}$, $f = 5.0 \text{ kHz}$.

Source: The author

Figure 36: Velocity profile of the jet induced by the serpentine serrated electrode DBD-PA, at the peak of the exposed electrode, $V = 20.0 \text{ kV}$, $f = 5.0 \text{ kHz}$.

Source: The author

Figure 37: Velocity profile of the jet induced by the serpentine serrated electrode DBD-PA, at the valley of the exposed electrode, $V = 20.0 \text{ kV}$, $f = 5.0 \text{ kHz}$.

Source: The author

These patterns observed in the jet velocity profiles can also be inferred from visualization of the plasma glow discharge. Figure 38 (a) shows the discharge pattern produced by the square serrated electrode. As previously stated, the teeth corners produce a more intense discharge due their pointy geometry (more intense light spots can be observed at this area). The jet produced at the corners is partially directed towards the valleys of the exposed electrode, creating a trapezoidal spread pattern at each tooth of the exposed electrode. Figure 38 (b) shows the discharge pattern produced by the double-serpentine serrated electrode. The peaks of the exposed electrode produce a more intense plasma discharge, but there is also a weaker discharge between the teeth of the exposed electrode.

Figure 38: Plasma discharge pattern at the: (a) square serrated electrode; (b) double-serpentine electrode.

Source: The author

3.2.2 Degradation of the plasma actuator

After several minutes of plasma discharge, it can be observed that the polyimide surface becomes opaque in the gap region where plasma is formed (Figure 39). This is an indication of chemical degradation of the polyimide film when exposed to the plasma.

Figure 39: Opacity observed at the gap region in the polyimide surface

Source: The author

This region is believed to be weakened with the plasma exposure, which changes its electrical properties, mainly its dielectric strength and dielectric constant. When the dielectric is broken, an electric arc is produced, burning the polyimide layers in its path (Figure 40).

Figure 40: Burned spot caused by electric arc

Source: The author

According to Houser (2013), polymeric dielectric layers, such as polyimide film, have poor resistance to plasma environments and can suffer degradation during extended actuation periods. This degradation can be perceived by the changing over time of operational properties and performance of a DBD-PA subject to continuous actuation. For example, power consumption and capacitance are increased along the operational life of a DBD-PA made of copper foil electrodes and polyimide film. These changes are due to both polyimide degradation and copper oxidation, since the ozone produced during actuation is a powerful oxidant (HOUSER, 2013).

In the case of handmade DBD-PAs, like the ones used in the experiments presented here, degradation is also associated with manufacturing imperfections. Although handmade DBD-PAs made of polyimide and copper self-adhesive tapes are inexpensive and simple to manufacture, these imperfections impose operational and performance limitations and do not guarantee repeatability and reproducibility (HOUSER, 2013). Geometrical imperfections like sharp points and wrinkles in the electrodes leads to intense charge concentration, which can cause arcing and dielectric damage (HOUSER, 2013). In addition, handmade DBD-PAs can have air pockets between layers, which can lead to plasma production inside the actuator, damaging the dielectric layers (HOUSER, 2013).

In order to overcome these problems, Houser (2013) suggests two solutions: a protective coating of the electrodes and a microfabrication method of DBD-PAs based on photolithographic deposition of a metallic film onto borosilicate glass substrates. This process of manufacturing also allows the construction of complex electrode geometries, which is difficult to obtain by hand without significant imperfections (HOUSER, 2013). Besides, the borosilicate glass is considerably more resistant to plasma environments than polymers.

Despite these problems associated with handmade DBD-PAs, manufactured with copper foil and polyimide self-adhesive tapes, the experiments presented within the following chapters are made with these handmade DBD-PAs, due to simplicity and lower costs. Therefore, the results presented at chapter 4 and chapter 5 are somehow affected by these material and manufacturing issues, but are sufficient to prove the proposed concepts in a laboratory scale.

4 DBD-PA APPLIED TO FLAP SIDE EDGE

As stated in chapter 2, based on the concepts presented by Yong, Xunnian and Dejiu (2013) and Hasebe, Naka and Fukagata (2011), a similar concept based on the combination of Coandă effect around a rounded flap tip and the blowing produced by plasma actuators was tried here. The objective was to produce a counter vortex at the flap side edge, in order to reduce the magnitude of the vortices responsible for the noise generation, thus reducing the noise level.

4.1 Experimental set-up and methodology

The experiments were conducted at the LAE-1 wind tunnel facilities (Figure 41). This wind tunnel was initially conceived for automobilistic aerodynamic testing, being now a multi-task facility mainly focused in aeronautical aerodynamic testing (CATALANO, 2001; CATALANO, 2004; SANTANA et al., 2014).

Figure 41: LAE-1 wind tunnel dimensions

Source: Santana et al. (2014)

It is a closed circuit low-speed wind tunnel, with a closed test section of 1.29 m height, 1.67 m width and 3 m length. The eight-blade fan driven by an 110 HP AC electric motor induces a maximum airspeed of 50 m/s, with low turbulence level (up

to 0.25%) is provided by a combination of two screen meshes, low-drag corner vanes, high-efficiency rotor blades and carefully designed low-angle diffusers (CATALANO, 2001; CATALANO, 2004; SANTANA et al., 2014). The LAE-1 wind tunnel was recently updated to perform aeroacoustic testing, receiving melamine foam cover in the walls A and B from the Figure 42, a foam filling of the gap between the fan blades and the wall at the position C and an acoustic baffle at the position D (SANTANA et al., 2014). These treatments were able to reduce the background noise in 5 *dB* and practically remove the tonal peaks of the fan, also reducing the turbulence level to 0.21%.

Figure 42: LAE-1 wind tunnel regions that received acoustic treatment

Source: Santana et al. (2014)

Details on the model tested and the instrumentation used for acoustic and pressure measurements are given in the next subsections.

4.1.1 Plasma generator

The apparatus used for generating the high voltage necessary for inducing the plasma discharge was the same described at the chapter 3. For further information on this topic, please refer to subsection 3.1.1.

4.1.2 Model

The flap scaled model used is representative of a conventional aircraft flap. It was designed and built by Giraldo (2019) for his Master's research. It was built by assembling laser cutted MDF ribs, steel spars and an aluminum alloy skin. At 10 *mm* from the flap tip (Figure 43), 57 pressure taps distributed chordwise along the flap surface are connected to plastic tubes that passes inside the flap. The flap section and the location of the pressure taps are displayed at Figure 44. The flap chord has 700 *mm* in order to increase the Strouhal and Reynolds numbers, since scaling is a problem in aeroacoustic wind tunnel testing, and the span has 700 *mm*.

Figure 43: Scheme of the pressure taps spanwise location

Source: The author

Figure 44: Flap section and location of the pressure taps

Source: The author, made with data from Giraldo (2019)

In order to induce a Coandă effect at the flap tip with the ionic blowing from the DBD-PAs, a rounded tip for the flap model (Figure 45) was designed and built. This tip was made of PLA through fused filament fabrication (FFF) (Figure 46) and have received a finishing with primer, sandpaper and painting. It has a hollow section for both material saving and housing the wires. Two circular holes and a central joint are used to position and fix the rounded tip at the flap model.

Figure 45: CAD model of the rounded flap tip

Source: The author

The DBD-PAs were handmade with three layers of polyimide self-adhesive tape between the electrodes and one layer of polyimide tape as substrate. The exposed electrode has 5 *mm* width and 20 *mm* length, whereas the encapsulated electrode has 10 *mm* width and 20 *mm* length. Both electrodes were made of copper self-adhesive tape with straight edges and the gap between the electrodes was of 1*mm*. The wires were attached to the electrodes by soldering.

Figure 46: (a) PLA made rounded tip during the finishing process; (b) Installation of a DBD-PA in the rounded tip

Source: The author

Four configurations were tested, varying the installation position of the DBD-PAS on the flap rounded tip. In each position, two DBD-PAs were connected in parallel, one in the suction side, blowing spanwise away from the flap tip and the other in the pressure side, blowing spanwise towards the flap root (Figure 48). The position of the electrodes for each one of four configurations are presented at Table 2, with *x* and *y* defined in Figure 47.

Finally, the flap was fixed to the turning table at the middle of the wind tunnel test section, facing the microphone array (Figure 49). The DBD-PA wires and the pressure tubes pass through the model out of the tunnel.

Figure 47: Definition of *x* and *y* of the Table 2

Source: The author

Table 2: DBD-PAs position on the flap rounded tip (each position has two DBD-PA, one at suction side, one at pressure side)

Position	x [mm]	y [mm]
1	50	0
2	270	0
3	50	400
4	270	250

Source: The author

Figure 48: DBD-PAs connected in parallel

Source: The author

Figure 49: Flap model installed in the wind tunnel test section

Source: The author

4.1.3 Acoustic measurements

Since the LAE-1 is a hard-wall closed test section wind tunnel, the acoustic measurements were carried out using a phased array technique to improve signal to noise ratio. The microphone array used consists of 61 G.R.A.S. 46BD microphone sets (which combine a $1/4$ in pressure microphone 40BD and a $1/4$ in preamplifier 26CB), flush mounted without grid at the test section side-wall, distributed in a modified spiral geometry (Figure 50) optimized for achieving a high frequency range with minimum beamwidth and side-lobe contamination (FONSECA et al., 2010).

Figure 50: Microphone array geometry.

Source: Pereira (2018)

These microphones have a frequency range of 4 kHz to 70 kHz ($\pm 2\text{ dB}$), a dynamic range of 166 dB , and a calibrated sensitivity of 1.5 to 2.6 mV/Pa (obtained with a NC-74

calibrator, which produces a 1.0 kHz , 1.0 Pa reference pressure fluctuation). This set of configurations and geometry warrants an array beamwidth smaller than 100 mm for frequencies above 400 Hz (PAGANI JÚNIOR, 2014).

The 61 microphone signals are synchronized and acquired with a National Instruments NI PXIe system composed of: PXIe 1082 chassis; PXIe-8135 controller for synchronization, triggering and control of acquisition boards; four PXIe-4497 boards for IEPE voltage measurements up to 204.8 kS/s and synchronized acquisition of 16 channels each; PXIe-8430 board for serial communication and PXIe-6341 board for multifunction acquisition of analog and digital I/O at 500 kS/s .

Data acquisition, processing and storage are managed by a MATLAB set of codes created and described by Pagani Júnior (2014). The acquisition code receives the synchronized measurements from the NI PXIe system, with data from the microphones and from the DP-Calc 8705 Micromanometer, and manual inputs of temperature, atmospheric pressure and relative humidity, read from analog instruments. All these data and informations about the model are stored in a Hierarchical Data Format (HDF5) file.

Then, these raw data files were processed with a frequency domain beamforming code implemented by Pagani Júnior (2014). This code performs a Fourier transform of microphone time history, applying Welch's methodology with 50% of block overlap and Hanning window, correcting the power by factor of $8/3$. This process is repeated for all the microphones in order to create a Cross Spectral Matrix (CSM), from which conventional beamforming calculations are made through a spatial filter within a selected potential source location, using steering vector normalization (PAGANI JÚNIOR, 2014; PEREIRA, 2018).

4.1.4 Pressure measurements

The pressure measurements at the model were made through a Scanivalve ZOC-33/64PxX2 electronic pressure scanning module. It has a 2.5 kPa full-scale range, 3.75 Pa accuracy and a 40 kHz scan rate. The tubes coming from the pressure taps were connected to the ScaniValve module, which communicated with a computer for the data acquisition through FTP protocol.

The dynamic pressure of the wind tunnel flow was measured by a Pitot tube and a static pressure tap both connected to a micromanometer DP-Calc 8705. It has a full-scale range of -1.245 kPa to 3.735 kPa , with accuracy of 1% of the reading $\pm 1\text{ Pa}$. The micromanometer acquisition was made by the National Instruments PXIe system described at subsection 4.1.3.

4.1.5 Experimental procedures

All the tests were carried out with the angle of attack set to 26° . This choice was made to achieve the same aerodynamic loading the flap would have if the complete multi-element wing were present at zero angle of attack (GIRALDO, 2019). For further details on this consideration, refer to Giraldo (2019).

The acoustic array measurements were made with a 102400 Hz sample rate during 20 s of measurement time. Each one of the four configurations was tested for all the combinations listed at Table 3.

Table 3: Flap side edge test matrix

	$Re = 1.12 \times 10^6$, $M = 0.08$	$Re = 5.76 \times 10^5$, $M = 0.04$
α	26°	26°
Position	1 and 2	3 and 4
V_m	30 V	30 V
f	3.0, 4.0, 5.0, 6.0, 7.0 and 7.9 kHz	3.0, 4.0, 5.0, 6.0, 7.0 and 7.9 kHz
F	10 Hz	10 Hz
D.C.	50%, 75% and 100%	50%, 75% and 100%
Measurements	Acoustic array and chordwise surface pressure	Acoustic array and chordwise surface pressure

Source: The author

4.2 Results and discussion

The raw measurements obtained from the experiments were processed, as explained at section 4.1, and the results are presented and discussed in the following subsections.

4.2.1 DBD-PA self noise

As observed by Roth, Sherman and Wilkinson (1998), a strong audible tone is produced at the plasma driving frequency. Thus, the first measurements carried out refer to the plasma actuator self-noise (wind off). The noise spectra of the DBD-PAs installed at the flap rounded tip are showed in Figure 51.

In addition to the tone in the driving frequency of the plasma, its harmonics are also observed. The peaks are slightly influenced by the duty cycle percentage, but in general the broadband component is alleviated when the DBD-PAs are operating at unsteady mode. Thus, the unsteady operation can be a way to reducing the plasma self-noise. Another solution would be operating the DBD-PA at an inaudible frequency, but with the geometry and the HFHVPS optimized for this very high frequencies. These very high frequencies, however, can introduce more electromagnetic noise and loss of efficiency, so this trade off must be taken into account.

Figure 51: Noise generated by the two DBD-PAs installed at the flap tip, without airflow within the wind tunnel. $V_{in} = 30V$

Source: The author

Initially it was believed that part of this self-noise observed could be a result of interactions between the electromagnetic noise emitted by the DBD-PAs and the acoustic measurement system. This supposition was then tested by blocking the microphone array with a wood panel and operating the DBD-PAs inside an acoustic anechoic box Figure 52. These tests showed a significant reduction of the measured noise (Figure 53), thus indicating that the self-noise showed at Figure 51 is mostly acoustic. If this self-noise were due to electromagnetic emissions, this reduction would not have been observed in the anechoic test. Although, it can be observed that the tonal peaks at the DBD-PA operating frequency and its harmonics are not totally muffled by the anechoic box, thus indicating some electromagnetic contamination of the measurements at these particular frequencies.

Figure 52: Setup for testing the electromagnetic noise contribution to the self-noise observed

Source: The author

Figure 53: Noise spectra by the DBD-PAs inside and outside the anechoic box, $f = 5.0kHz$, $V_{in} = 30V$, $D.C. = 100\%$

Source: The author

4.2.2 Acoustic array and surface pressure measurements

The overall sound pressure level difference between each configuration and the baseline ($\Delta OASPL$) was computed from the acquired data for the full range of frequencies measured. In order to eliminate the effect of the DBD-PA self noise, which is believed to be weaker and out of the range of the flap noise spectra at flight conditions, the $\Delta OASPL$ was also computed truncating the data above the DBD-PA operating frequency

(Δ OASPL*). These values are shown at Table 4 and Table 5. The tables also show how much this truncation is significant, displaying the difference in the overall sound pressure level between the truncated and the untruncated data, for each configuration.

Table 4: OASPL difference between the flap with and without DBD-PA, for the configurations tested at $Re = 1.12 \times 10^6$, $M = 0.08$

Position [-]	f [kHz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
1	3.0	100	1.35	0.55	-1.83
1	3.0	75	1.57	0.88	-1.71
1	3.0	50	1.41	0.94	-1.49
1	4.0	100	1.02	0.61	-1.00
1	4.0	75	1.23	0.92	-0.90
1	4.0	50	1.03	0.81	-0.81
1	5.0	100	0.95	0.70	-0.68
1	5.0	75	1.06	0.91	-0.57
1	5.0	50	0.90	0.79	-0.54
1	6.0	100	0.86	0.61	-0.57
1	6.0	75	1.10	0.97	-0.44
1	6.0	50	0.84	0.78	-0.37
1	7.0	100	0.71	0.42	-0.52
1	7.0	75	0.84	0.75	-0.33
1	7.0	50	0.79	0.77	-0.26
1	7.9	100	0.92	0.76	-0.37
1	7.9	75	1.03	0.94	-0.30
1	7.9	50	0.70	0.69	-0.22
2	3.0	100	3.00	2.03	-1.99
2	3.0	75	5.30	4.63	-1.69
2	3.0	50	1.35	0.74	-1.64
2	4.0	100	0.93	0.18	-1.34
2	4.0	75	1.08	0.56	-1.11
2	4.0	50	1.31	1.06	-0.84
2	5.0	100	0.51	0.07	-0.87
2	5.0	75	0.82	0.57	-0.68
2	5.0	50	2.29	2.23	-0.49
2	6.0	100	0.42	0.11	-0.62
2	6.0	75	0.62	0.45	-0.48
2	6.0	50	2.20	2.16	-0.35

Table 4 continued from previous page

Position [-]	f [kHz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
2	7.0	100	0.40	0.30	-0.33
2	7.0	75	0.73	0.72	-0.25
2	7.0	50	1.71	1.73	-0.21
2	7.9	100	0.34	0.31	-0.23
2	7.9	75	0.97	0.97	-0.21
2	7.9	50	1.88	1.89	-0.19

Source: The author

Analyzing the data shown at these tables, its evident that the positions 1 and 2, tested at higher Reynolds, were not effective in reducing aerodynamic noise. In fact, they were all prejudicial, since the overall sound pressure level was increased when the DBD-PAs were activated for all the combinations for these conditions. The worst case for each position was selected and the sound spectra, PSD difference and chordwise pressure distribution for these conditions are shown at Figure 54, Figure 55, Figure 56, Figure 57, Figure 58 and Figure 59.

Figure 54: Noise spectra, DBD-PAs on flap rounded tip at position 1, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 1.12 \times 10^6$, $M = 0.08$.

Source: The author

For the position 1, the worst configuration tested was with a frequency of 6.0 kHz and modulated at $F = 10 \text{ Hz}$, with 75% of duty cycle. From Figure 54 and Figure 55, it can be seen that the plasma actuation has increased the broadband noise for most frequencies.

Figure 55: PSD difference when DBD-PAs on flap rounded tip at position 1 are activated, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 1.12 \times 10^6$, $M = 0.08$.

Source: The author

Figure 56 depicts the effect of plasma actuation on the pressure distribution affected by the vortices system. A small rise in a suction point was observed at the region where the DBD-PAs were installed, whereas the pressure side was affected downstream the plasma actuators, where the pressure coefficient was approached to zero when DBD-PAs were activated in relation to the baseline condition.

Figure 56: Chordwise pressure distribution over the flap tip section, DBD-PAs on flap rounded tip at position 1, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 1.12 \times 10^6$, $M = 0.08$.

Source: The author

For the position 2, the worst configuration tested was with a frequency of 3.0 kHz

and modulated at $F = 10 \text{ Hz}$, with 75% of duty cycle. From Figure 57 and Figure 58, it can be seen that the plasma actuation in these conditions has introduced some tonal noise with harmonics of the frequencies of 520 Hz and 1080 Hz .

Figure 57: Noise spectra, DBD-PAs on flap rounded tip at position 2, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 1.12 \times 10^6$, $M = 0.08$.

Source: The author

Figure 58: PSD difference when DBD-PAs on flap rounded tip at position 2 are activated, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 1.12 \times 10^6$, $M = 0.08$.

Source: The author

Figure 59 depicts the effect of plasma actuation on the pressure distribution affected by the vortices system. A small rise in the peak of suction was observed. At the region where the DBD-PAs were installed, the vortex were reduced (there is a reduction of the

suction from x/c 0.4 to 0.7). The pressure side upstream the DBD-PAs was also affected, rising its pressure.

Figure 59: Chordwise pressure distribution over the flap tip section, DBD-PAs on flap rounded tip at position 2, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 1.12 \times 10^6$, $M = 0.08$.

Source: The author

In the case of positions 3 and 4, tested at lower Reynolds, Table 5 shows a more effective result of plasma actuation. This difference evidences the problem of the DBD-PA control authority loss when Reynolds number is increased.

Although the results for these cases are of overall sound pressure level reduction, the benefit is still marginal. The best configurations for each position were selected and the sound spectra, PSD difference and chordwise pressure distribution for these conditions are shown at Figure 60, Figure 61, Figure 62, Figure 63, Figure 64 and Figure 65.

Table 5: OASPL difference between the flap with and without DBD-PA, for the configurations tested at $Re = 5.76 \times 10^5$, $M = 0.04$.

Position [-]	f [kHz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
3	3.0	100	3.22	0.01	-4.19
3	3.0	75	2.71	-0.16	-3.86
3	3.0	50	2.31	-0.04	-3.33
3	4.0	100	1.98	-0.02	-2.61
3	4.0	75	1.41	-0.23	-2.24
3	4.0	50	1.11	-0.17	-1.88
3	5.0	100	0.70	-0.17	-1.30

Table 5 continued from previous page

Position [-]	f [kHz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
3	5.0	75	0.81	0.12	-1.13
3	5.0	50	0.07	-0.52	-1.03
3	6.0	100	0.16	-0.30	-0.76
3	6.0	75	0.01	-0.34	-0.65
3	6.0	50	-0.13	-0.39	-0.56
3	7.0	100	-0.17	-0.25	-0.31
3	7.0	75	-0.09	-0.15	-0.29
3	7.0	50	-0.17	-0.22	-0.27
3	7.9	100	0.06	0.04	-0.21
3	7.9	75	-0.25	-0.27	-0.22
3	7.9	50	-0.37	-0.39	-0.22
4	3.0	100	2.99	-0.75	-4.73
4	3.0	75	3.05	-0.10	-4.14
4	3.0	50	2.21	-0.57	-3.77
4	4.0	100	1.98	-0.34	-2.93
4	4.0	75	1.63	-0.28	-2.51
4	4.0	50	1.05	-0.49	-2.14
4	5.0	100	0.93	-0.12	-1.49
4	5.0	75	0.46	-0.44	-1.34
4	5.0	50	0.31	-0.38	-1.12
4	6.0	100	0.30	-0.26	-0.87
4	6.0	75	0.13	-0.27	-0.70
4	6.0	50	-0.28	-0.61	-0.62
4	7.0	100	-0.17	-0.26	-0.31
4	7.0	75	-0.09	-0.14	-0.28
4	7.0	50	-0.27	-0.31	-0.27
4	7.9	100	-0.14	-0.14	-0.19
4	7.9	75	-0.50	-0.51	-0.20
4	7.9	50	-0.05	-0.05	-0.20

Source: The author

For the position 3, the best configuration tested was with a frequency of 5.0 kHz and modulated at $F = 10 Hz$, with 50% of duty cycle. From Figure 60 and Figure 61, it can be seen that some marginal improvement was achieved. For some frequencies, the PSD difference was up to $-5 dB$, but for other frequencies, a rise of up to 3 dB was produced.

Figure 60: Noise spectra, DBD-PAs on flap rounded tip at position 3, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 5.76 \times 10^5$, $M = 0.04$.

Source: The author

Figure 61: PSD difference when DBD-PAs on flap rounded tip at position 3 are activated, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 5.76 \times 10^5$, $M = 0.04$.

Source: The author

Figure 62 depicts the effect of plasma actuation on the pressure distribution affected by the vortices system. Practically no effect on the peak of suction was observed. At the region where the DBD-PAs were installed, the pressure coefficient was augmented from x/c 0.2 to 0.4 at the pressure side. The vortex downstream the DBD-PAs was shifted towards the leading edge, as can be seen by the suction region from the Figure 62.

Figure 62: Chordwise pressure distribution over the flap tip section, DBD-PAs on flap rounded tip at position 3, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 5.76 \times 10^5$, $M = 0.04$.

Source: The author

Figure 63: Noise spectra, DBD-PAs on flap rounded tip at position 4, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 5.76 \times 10^5$, $M = 0.04$.

Source: The author

Finally, considering the position 4, the best configuration tested was with a frequency of 3.0 kHz and steady actuation (100% of duty cycle). From Figure 63 and Figure 64, it can be seen that some marginal improvement was achieved, mostly between 720 Hz and 1120 Hz . For some frequencies, the PSD difference was up to -5 dB , but for other frequencies, a rise of up to 2 dB was produced.

Figure 64: PSD difference when DBD-PAs on flap rounded tip at position 4 are activated, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 5.76 \times 10^5$, $M = 0.04$.

Source: The author

Figure 65 shows the effect of plasma actuation on the pressure distribution affected by the vortices system. The peak of suction was slightly modified. At the region where the DBD-PAs were installed, the suction was augmented from x/c 0.4 to 0.7 at the suction side. The vortex apparently was slightly intensified and shifted towards the leading edge.

Figure 65: Chordwise pressure distribution over the flap tip section, DBD-PAs on flap rounded tip at position 4, $V_{in} = 30V$. $\alpha = 26^\circ$, $Re = 5.76 \times 10^5$, $M = 0.04$.

Source: The author

4.2.3 Summary of the results

In this chapter the DBD-PA self-noise characteristics were presented, as well the results of applying the DBD-PAs at a flap rounded tip in terms of overall sound pressure level, noise spectra and chordwise pressure distribution at the flap tip. The results showed that:

- DBD-PA self-noise is significant and, for the measurements carried out, it was almost purely acoustic (electromagnetic noise has not affected the measurements in the frequencies below the DBD-PA operating frequency).
- DBD-PA self-noise has intense tones at the AC frequencies and its harmonics.
- DBD-PA self-noise has increasing broadband noise with the sound frequency after the first tonal peak.
- The DBD-PA self-noise problem could be solved by optimizing the system for operating at inaudible frequencies (considering efficiency losses and increasing in electromagnetic emissions).
- DBD-PA applied to the rounded flap tip was more effective at lower Reynolds and Mach number, due to the small control authority of the DBD-PAs (kinetic energy of the external flow is much greater than the kinetic energy introduced by the DBD-PA jet).
- DBD-PA at the flap rounded tip has increased the OASPL for most configurations tested, but was able to marginally reduce the OASPL for some configurations, indicating its potential to affect the noise generation mechanism, since the pressure distribution over the flap tip was also affected by the DBD-PA activation (side edge vortices were shifted).

5 DBD-PA APPLIED TO LEADING EDGE SLAT

Distributed two-dimensional sound sources of relatively low intensity, when integrated along its span, produce significant noise levels comparable to those generated by three-dimensional mechanisms (ROGER; PERENNES, 2000). Noise generated by three-dimensional flows are more easily controlled, while noise generated by two-dimensional sources are inherent to the high-lift devices, being of fundamental importance the study of these two-dimensional effects (ROGER; PERENNES, 2000). This way, the experiments with DBD-PAs installed at the leading-edge slat were conducted in a two-dimensional multi-element wing. The experimental set-up, the methodology and the results are shown and commented in this chapter.

5.1 Experimental set-up and methodology

Two types of tests were executed regarding the leading-edge slat equipped with DBD-PAs: smoke flow visualization and acoustic array measurements. These tests are described in the following sections.

5.1.1 Flow visualization

In order to have a proof of concept, a smoke flow visualization experiment was executed before implementation of the acoustic tests. These visualisation test was carried out in an open circuit vertical wind tunnel at the Aeronautical Engineering Department, at the University of São Paulo (Figure 66). This wind tunnel is equipped with a Preston and Sweeting (1943) smoke generator connected to a rake of tubes, and operates at very low wind speed (in the order of 2.0 m/s). It has a test section of 700 mm length, 350 mm width and 150 mm depth, with fluorescent tubes in its lateral walls that create a light sheet in the plane of the smoke filaments.

Figure 66: Vertical wind tunnel, smoke generator and plasma generator.

Source: The author

First, a scaled model of the complete multi-element wing was made of ABS through FFF (Figure 67). The model has a 150 mm span and a full-extended chord of 498 mm , and is attached to an aluminum shaft used for fixation within the test section.

Figure 67: Model of the multi-element wing in the smoke wind tunnel test section

Source: The author

A DBD-PA was handmade with three polyimide self-adhesive film layers between the

straight grounded electrode (10 *mm* wide, 140 *mm* length, made of copper self-adhesive tape) and the straight exposed electrode (5 *mm* wide, 140 *mm* length, made of copper self-adhesive tape). The gap between the electrodes was of 1 *mm*. The DBD-PA was installed at two different positions: near the reattachment region and at the slat cusp (Figure 68).

Figure 68: DBD-PA installed on the slat model for concept proof experiments: at the cusp (left) and near the reattachment (right)

Source: The author

The experiments consisted of a photographic register with the DBD-PA deactivated and activated for comparison of the streamlines (smoke filaments). The HFHVPS is the same presented in subsection 3.1.1. The operational parameters of the HFHVPS was: $V_{in} = 25 \text{ V}$, $f = 6.0 \text{ kHz}$ (hence $V = 19.7 \text{ kV}$, according to Figure 25) and $D.C. = 100\%$. The wind speed was of about 2.0 *m/s*.

5.1.2 Acoustic array measurements

The acoustic measurements were carried out in the same wind tunnel facilities and through the same acoustic array techniques described at section 4.1 and subsection 4.1.3.

The DBD-PAs were installed individually at three positions (Figure 69) along the slat of a two-dimensional multi-element wing model (Figure 70). This model is representative of a commercial aircraft wing. The wing model has 500 *mm* chord (stowed) and 1340 *mm* span. The main element chord is 350 *mm*, the flap chord is 150 *mm* and the slat chord is 85 *mm*. Single slotted flaps are attached to the main element by steel brackets with a deflection angle of 35°. The slotted leading edge slat is divided in three parts along its span. These parts are attached by steel brackets to the main element and the relative position between adjacent parts is maintained by positioning pins. The central part of the slat was made of ABS through FFF in order to have an insulating substrate for

receiving the DBD-PA, since the original model is made in conductive material (aluminum alloy).

Figure 69: Positions in which the DBD-PA will be tested on the slat.

Source: The author

Figure 70: Multielement wing model within the wind tunnel test section.

Source: The author

In order to evaluate the sound emissions from the central portion of the slat only, far from the model endings, the extreme portions of the slat were equipped with PLA slat cove fillers (Figure 71), made through FFF, which have the shear layer contour for zero angle of attack (obtained through CFD) and zig-zag boundary layer trip strip at their

suction surface. These devices were intended to reduce contamination in the spectrum from noise sources outside the region of interest (Figure 72).

Figure 71: Cove fillers and DBD-PA installed at the slat.

Source: The author

Figure 72: Region of interest for the beamforming calculations.

Source: adapted from Pereira (2018)

The tests were executed at zero angle of attack, since according the results obtained by Pereira (2018), it is the angle in which more intense noise is produced.

First, the straight electrode DBD-PA, which is the simpler one, was tested at the three positions. Since positions 2 and 3 (Figure 69) were not effective for noise reduction, the remaining geometries of DBD-PA were installed just at the position 1. This was made in order to reduce the test matrix (Table 6), thus optimizing the use of wind tunnel time.

Table 6: Slat test matrix

	Straight electrode	Square serrated electrode	Double-serpentine serrated electrode
Re	7.57×10^5	7.57×10^5	7.57×10^5
M	0.08	0.08	0.08
α	0°	0°	0°
Position	1, 2 and 3	1	1
V_{in}	30 V	30 V	30 V
f	3.0, 4.0, 5.0 and 6.0 kHz	3.0, 4.0, 5.0 and 6.0 kHz	3.0, 4.0, 5.0 and 6.0 kHz
F	306 and 1835 Hz	306 and 1835 Hz	306 and 1835 Hz
D.C.	50%, 75% and 100%	50%, 75% and 100%	50%, 75% and 100%
Measurements	Acoustic array	Acoustic array	Acoustic array

Source: The author

The model was set to zero angle of attack and the wind tunnel to an average speed to 27.4 m/s . For each DBD-PA configuration, the acquisition of the 61-microphone array data was made at a sample rate of 102400 Hz during an acquisition time of 20.0 seconds. All the combinations of electrode geometry, DBD-PA position, voltage input, frequency of AC voltage output, frequency of output modulation and duty cycle of output modulation presented at Table 6 were tested using this procedure. The modulation frequency of 306 Hz was chosen in order to match the unitary Strouhal, considering the slat chord, the wind speed and the modulation frequency. The modulation frequency of 1835 Hz was chosen to match a sub-harmonic of the slat tonal noise of the slat measured by Pereira (2018).

The processed results of these measurements are presented in the next section.

5.2 Results and discussion

5.2.1 Flow visualization

As can be seen in Figure 73, the DBD-PA installed at the slat cusp was able to shift the reattachment position when activated. This shows the potential of the DBD-PA to interfere with the slat noise generation mechanism. This ability was acoustically assessed in the next experiments.

Figure 73: Reattachment displacement caused by the DBD-PA, proofing the concept proposed

Source: The author

The visualization of the flow conditions with DBD-PA installed at the surface of slat cove are not presented here, since no difference between the conditions with and without plasma actuation was observed. Although these position of installation, at first, was not effective, it was not discarded for the acoustic experiments. This choice was made because of the diminished scale of the model relative to the unscaled DBD-PA, which did not allow to apply the DBD-PA at the reattachment point for the visualization experiments. Figure 74 depicts the glow discharge pattern of the DBD-PA activated at the slate cove.

Figure 74: Glow discharge pattern observed at the DBD-PA installed near the reattachment point.

Source: The author

5.2.2 Acoustic array measurements

Since the model construction did not allow a flush mounted installation of the DBD-PA and its wiring, each configuration had its acoustic measurement baseline made with the DBD-PA deactivated. Comparisons for evaluating plasma actuation effects were made in relation to these respective baseline conditions, and not relative to the clean baseline condition.

Figure 75 and Figure 76 show the increase in noise caused by the installation of the DBD-PAs in relation to the clean baseline configuration. All the peaks are amplified by the presence of the DBD-PA and its wiring (even the most portion of the wiring being passed inside the cove fillers). A possible explanation for it is that the installation of the DBD-PA thickened the cusp and the trailing edge and exposed part of the blunt wires to the airflow at the bracket region, increasing noise created by vortex shedding from separated regions.

Figure 75: Noise spectra of the baseline configurations, DBD-PA on each position of the slat, but deactivated. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Figure 76: PSD difference between each baseline configuration and the clean baseline. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

After measuring data and computing the beamforming from all the combinations of configurations listed at Table 6, the overall sound pressure level difference between each configuration and the respective baseline was computed. This OASPL differences are shown at Table 7, Table 8, Table 9, Table 10 and Table 11.

From these tables, the best configurations were chosen for the positions in which there was noise reduction and the worst configurations were chosen for the positions in which the noise emissions increased. For these selected configurations, the sound spectra

and PSD difference were plotted and analyzed. As for the flap results, these plots were truncated at the plasma driving frequency in order to not pollute the plots with the DBD-PA self noise, which could be eliminated by proper setting of the DBD-PA system in order to operate outside audible frequencies.

Table 7: OASPL difference between the slat with the DBD-PA activated and deactivated, at the region of interest. Straight DBD-PA installed at position 1, operating at $V_{in} = 30V$. $Re = 7.57 \times 10^5$, $M = 0.08$.

f [kHz]	F [Hz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
3.0	-	100	-2.36	-2.88	-0.87
4.0	-	100	-2.70	-2.91	-0.48
5.0	-	100	-2.68	-2.79	-0.30
6.0	-	100	-2.58	-2.66	-0.21
3.0	306	75	-2.48	-2.97	-0.84
4.0	306	75	-2.86	-3.07	-0.48
5.0	306	75	-2.73	-2.83	-0.29
6.0	306	75	-2.79	-2.86	-0.20
3.0	306	50	-2.85	-3.29	-0.79
4.0	306	50	-3.12	-3.32	-0.47
5.0	306	50	-3.10	-3.20	-0.28
6.0	306	50	-2.78	-2.84	-0.19
3.0	1835	75	-2.60	-3.21	-0.96
4.0	1835	75	-3.02	-3.27	-0.52
5.0	1835	75	-2.96	-3.09	-0.31
6.0	1835	75	-2.89	-2.98	-0.22
3.0	1835	50	-2.89	-3.35	-0.81
4.0	1835	50	-2.88	-3.08	-0.47
5.0	1835	50	-2.91	-3.01	-0.29
6.0	1835	50	-3.07	-3.14	-0.21

Source: The author

The straight electrode at the position 1 produced the best results, slightly reducing broadband noise and considerably reducing tonal noise. The best result was produced by the DBD-PA operating at $f = 3.0 \text{ kHz}$, modulated by a square wave with 1835 Hz and 50% of duty cycle. It was able to reduce 3.35 dB in the OASPL and 12 dB in the main

peak (Figure 77 and Figure 78).

Figure 77: Noise spectra, straight DBD-PA on slat at position 1, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Figure 78: PSD difference when straight DBD-PA on slat at position 1 are activated, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Table 8: OASPL difference between the slat with the DBD-PA activated and deactivated, at the region of interest. Straight DBD-PA installed at position 2, operating at $V_{in} = 30V$. $Re = 7.57 \times 10^5$, $M = 0.08$.

f [kHz]	F [Hz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
3.0	-	100	0.27	-0.08	-0.84
4.0	-	100	0.34	0.13	-0.54
5.0	-	100	0.17	0.01	-0.33
6.0	-	100	0.07	-0.06	-0.24
3.0	306	75	0.68	0.31	-0.86
4.0	306	75	2.29	2.22	-0.42
5.0	306	75	2.25	2.13	-0.29
6.0	306	75	2.17	2.05	-0.22
3.0	306	50	2.01	1.80	-0.70
4.0	306	50	2.05	2.00	-0.40
5.0	306	50	2.02	1.93	-0.26
6.0	306	50	1.95	1.85	-0.20
3.0	1835	75	1.96	1.65	-0.80
4.0	1835	75	2.23	2.05	-0.52
5.0	1835	75	2.14	1.94	-0.38
6.0	1835	75	1.93	1.22	-0.82
3.0	1835	50	1.96	1.73	-0.72
4.0	1835	50	2.10	1.95	-0.49
5.0	1835	50	1.99	1.81	-0.35
6.0	1835	50	2.09	1.93	-0.27

Source: The author

The straight electrode at the position 2 was not effective, having caused an increase in the OASPL for almost all the operational configurations. The worst result was produced by the DBD-PA operating at $f = 4.0 \text{ kHz}$, modulated by a square wave with 306 Hz and 75% of duty cycle. It has intensified both the broadband and the tonal noise, adding up to 6 dB in the PSD (Figure 79 and Figure 80).

Figure 79: Noise spectra, straight DBD-PA on slat at position 2, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Figure 80: PSD difference when straight DBD-PA on slat at position 2 are activated, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Table 9: OASPL difference between the slat with the DBD-PA activated and deactivated, at the region of interest. Straight DBD-PA installed at position 3, operating at $V_{in} = 30V$. $Re = 7.57 \times 10^5$, $M = 0.08$.

f [kHz]	F [Hz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
3.0	-	100	0.19	-0.03	-0.69
4.0	-	100	0.28	0.07	-0.55
5.0	-	100	0.13	0.04	-0.29
6.0	-	100	0.01	-0.06	-0.20
3.0	306	75	0.14	-0.07	-0.67
4.0	306	75	0.11	-0.04	-0.49
5.0	306	75	-0.11	-0.18	-0.29
6.0	306	75	-0.05	-0.11	-0.19
3.0	306	50	0.07	-0.10	-0.64
4.0	306	50	0.04	-0.08	-0.46
5.0	306	50	0.00	-0.05	-0.26
6.0	306	50	-0.12	-0.17	-0.17
3.0	1835	75	0.10	-0.13	-0.69
4.0	1835	75	0.26	0.10	-0.51
5.0	1835	75	-0.05	-0.14	-0.30
6.0	1835	75	-0.04	-0.10	-0.20
3.0	1835	50	0.17	-0.02	-0.65
4.0	1835	50	-0.05	-0.18	-0.48
5.0	1835	50	0.04	-0.02	-0.27
6.0	1835	50	0.04	-0.01	-0.18

Source: The author

The straight electrode at the position 3 produced marginal benefits, slightly reducing the OASPL. The best result was produced by the DBD-PA operating at $f = 4.0 \text{ kHz}$, modulated by a square wave with 1835 Hz and 50% of duty cycle and at $f = 5.0 \text{ kHz}$, modulated by a square wave with 306 Hz and 75% of duty cycle. It was able to reduce up to 4 dB in the PSD, but for most frequencies the difference was near zero (Figure 81 and Figure 82).

Figure 81: Noise spectra, straight DBD-PA on slat at position 3, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Figure 82: PSD difference when straight DBD-PA on slat at position 3 are activated, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Table 10: OASPL difference between the slat with the DBD-PA activated and deactivated, at the region of interest. Square serrated DBD-PA installed at position 1, operating at $V_{in} = 30V$. $Re = 7.57 \times 10^5$, $M = 0.08$.

f [kHz]	F [Hz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
3.0	-	100	-0.01	-0.35	-0.76
4.0	-	100	0.09	-0.05	-0.45
5.0	-	100	0.04	-0.03	-0.27
6.0	-	100	-0.10	-0.13	-0.16
3.0	306	75	0.25	-0.13	-0.79
4.0	306	75	0.34	0.22	-0.43
5.0	306	75	0.35	0.29	-0.25
6.0	306	75	0.20	0.18	-0.16
3.0	306	50	0.45	0.15	-0.72
4.0	306	50	0.27	0.18	-0.41
5.0	306	50	0.15	0.10	-0.25
6.0	306	50	0.00	-0.01	-0.15
3.0	1835	75	0.30	-0.25	-0.96
4.0	1835	75	0.15	-0.05	-0.51
5.0	1835	75	0.04	-0.03	-0.27
6.0	1835	75	0.09	0.07	-0.16
3.0	1835	50	0.32	-0.03	-0.77
4.0	1835	50	-0.19	-0.34	-0.46
5.0	1835	50	-0.03	-0.08	-0.25
6.0	1835	50	0.07	0.04	-0.16

Source: The author

The square serrated electrode at the position 1 also produced marginal benefits, slightly reducing the OASPL. The best result was produced by the DBD-PA operating at $f = 4.0 \text{ kHz}$ in steady mode ($D.C. = 100\%$). It was able to reduce up to 4 dB in the PSD, but for most frequencies the difference was near zero (Figure 83 and Figure 84).

Figure 83: Noise spectra, square serrated DBD-PA on slat at position 1, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Figure 84: PSD difference when square serrated DBD-PA on slat at position 1 are activated, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Table 11: OASPL difference between the slat with the DBD-PA activated and deactivated, at the region of interest. Double serpentine serrated DBD-PA installed at position 1, operating at $V_{in} = 30V$. $Re = 7.57 \times 10^5$, $M = 0.08$.

f [kHz]	F [Hz]	D.C. [%]	Δ OASPL [dB]	Δ OASPL* [dB]	OASPL difference due truncation [dB]
3.0	-	100	-0.64	-1.00	-0.77
4.0	-	100	-0.51	-0.64	-0.44
5.0	-	100	-0.54	-0.63	-0.29
6.0	-	100	-0.32	-0.35	-0.17
3.0	306	75	-0.71	-1.04	-0.75
4.0	306	75	-0.59	-0.71	-0.44
5.0	306	75	-0.68	-0.76	-0.28
6.0	306	75	-0.54	-0.57	-0.17
3.0	306	50	-0.60	-0.91	-0.72
4.0	306	50	-0.81	-0.94	-0.43
5.0	306	50	-0.81	-0.88	-0.27
6.0	306	50	-0.76	-0.80	-0.17
3.0	1835	75	-0.83	-1.32	-0.91
4.0	1835	75	-0.99	-1.18	-0.49
5.0	1835	75	-1.14	-1.25	-0.31
6.0	1835	75	-0.90	-0.95	-0.18
3.0	1835	50	-1.02	-1.40	-0.79
4.0	1835	50	-1.00	-1.15	-0.46
5.0	1835	50	-1.23	-1.33	-0.29
6.0	1835	50	-1.07	-1.12	-0.18

Source: The author

The double-serpentine serrated electrode at the position 1 was able to reduce up to 1.40 dB in the OASPL. The best result was produced by the DBD-PA operating at $f = 3.0 \text{ kHz}$, modulated by a square wave with 1835 Hz and 50% of duty cycle. The OASPL reduction was mainly due tonal peak attenuation, which was reduced in about 7.5 dB (Figure 85 and Figure 86).

Figure 85: Noise spectra, double-serpentine serrated DBD-PA on slat at position 1, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

Figure 86: PSD difference when double-serpentine serrated DBD-PA on slat at position 1 are activated, $V_{in} = 30V$. $\alpha = 0^\circ$, $Re = 7.57 \times 10^5$, $M = 0.08$.

Source: The author

From these results, it can be seen that the best DBD-PA configurations to reduce slat noise were that installed at position 1 (slat cusp). Initially, it was expected that the serrated configurations would produce the higher slat noise attenuation. However, the experiments have shown that the straight electrode was the most effective. This expectation was due the three-dimensional flow structures expected from the serrated configurations, that should be able to break spanwise coherence of pressure fluctuations. Although the straight electrode have been the most effective, it should be noted that this

configuration also had the most intense baseline noise, especially at the most intense peak. If the DBD-PA was perfectly flush mounted, the noise reduction of this configuration could be even higher.

The most effective result obtained for the straight electrode may be related to constructive issues, since all the DBD-PAs tested were handmade. Straight electrodes are easier to cut and align, so the plasma discharge produced by them is more efficient. In the case of the serrated electrodes, the manual alignment of the electrodes is not perfect and can severely impact the DBD-PA performance.

It has also to be highlighted that the most efficacious configuration was operating with 50% of duty cycle, thus consuming half the power of steady mode operation and producing less PA self noise.

6 CONCLUSIONS AND RECOMMENDATIONS

The DBD-PAs tested along this research were able to marginally reduce the aerodynamic noise produced by the flap and the slat, thus showing its potential to affect the high-lift noise generation mechanisms.

When applied to the flap side edge together with a rounded tip, most of the configurations tested have increased the noise. However, when operated at 3.0 kHz and 100% of duty cycle, it was able to reduce the overall sound pressure level in 0.75 dB , by changing the vortices behavior.

When applied to the slat cusp, the straight electrode DBD-PA was able to reduce up to 3.3 dB in the overall sound pressure level when operating at 3.0 kHz , modulated by a square wave with 1835 Hz and 50% of duty cycle. Applying the DBD-PA at the reattachment region showed no effectiveness in reducing slat noise. Other geometries of electrode applied to the slat cusp were somehow effective, but not as much as the straight electrode. This can be related to loss of efficiency in complex geometry DBD-PAs manually assembled.

The control authority of the DBD-PAs tested is poor, but could be improved by proper optimization of the DBD-PA geometry, material and electric circuit.

However, in the author's opinion, the technology of DBD-PAs is still far from being a feasible technical solution for aeronautical practical purposes. It lacks of control authority at real flight Reynolds, the materials used do not withstand plasma environments or high voltages and the manufacturing methods are critical for the DBD-PA performance. The safety of the DBD-PAs operation is also a critical issue for aeronautical applications. Even though a Faraday cage effect could protect equipment or fuel from electric discharges at the airframe surface, the risks of continuously producing very high voltages near the fuel tanks is a critical issue that may render unfeasible the aeronautical use of DBD-PAs, even more if the benefits provided by the DBD-PA operation are poor.

Besides, ozone emissions should be measured when studying DBD-PA applications, since these emissions are inherent to the DBD-PA operation and this gas is a pollutant at tropospheric altitudes.

Self-noise emissions (acoustic and electromagnetic) should also be considered for practical applications. A way to solve this could be designing a set of DBD-PA and HFHVPS optimized to operate at frequencies outside the audible spectrum.

Considering all these conclusions, the author would recommend the following advices for those researchers intending to develop future work in this area:

- Develop better processes and materials to manufacture the DBD-PAs, in order to overcome performance degradation due to imperfections and material degradation.
- Perform an experimental system identification relating inputs, geometry and outputs, in order to allow an optimization of the system and the implementation of a closed loop control system.
- Optimize the circuit to operate in frequencies outside the audible range, if possible.
- Perform a more complete jet profile mapping, sweeping a more discretized volume, and founding an analytical model from the data.
- Perform a jet profile mapping with external wind.
- Perform a detailed uncertainty analysis, since the marginal improvements obtained in some cases could be within the experimental errors, despite the large amount of acquired data samples used in this research.
- Perform real time measurements of voltage and current, simultaneously to other measurements, in order to evaluate the DBD-PA performance.
- Perform ozone emission measurements.
- Perform other forms of flow visualization in order to better understand how the DBD-PAs are affecting the complete flow field.
- Execute measurements with DBD-PAs in a flap rounded tip blowing the vortices away from the flap (instead of trying to produce counter vortices), as in the concept presented by Yong, Xunnian and Dejiu (2013).
- Repeat the measurements in the slat with a flush mounted configuration and better manufactured DBD-PAs.
- Execute measurements with DBD-PAs in other slat positions, as those presented by Yong, Xunnian and Dejiu (2013).

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Annex

ANNEX A – HIGH-FREQUENCY/HIGH-VOLTAGE AC POWER SUPPLY (HFHVPS) - ELECTRICAL DIAGRAM

The High-Frequency/High-Voltage AC Power Supply (HFHVPS) used in all the experiments presented in this dissertation was designed and built by Dr. José Antonio Garcia Croce, who kindly lend the equipment to the author. The electrical diagram of the HFHVS is presented in this annex (Figure 87). It is an inverter circuit, controlled by an Arduino Nano board, which produces a PWM square wave of high frequency that is transformed in a sinusoidal signal by the circuit. This AC low voltage is amplified by an ignition coil wich rises the voltage up to 20 kV . The HFHVPS relation between input and output voltage are shown at Figure 25.

Fonte: Croce (2018), personal communication ¹

ANNEX B – HIGH-FREQUENCY/HIGH-VOLTAGE AC POWER SUPPLY (HFHVPS) - ARDUINO CODE

The High-Frequency/High-Voltage AC Power Supply (HFHVPS) used in all the experiments presented in this dissertation was designed and built by Dr. José Antonio Garcia Croce, who kindly lend the equipment to the author. The Arduino code to control the HFHVS was implemented by Croce (2018)¹ and modified by the author of this dissertation to allow different PWM frequencies of the output signal. The original code is presented in this annex. Its output signal is modulated by a square wave with $F = 10Hz$. In order to test other output modulation frequencies, the modifications presented at Table 12 were made:

Table 12: Modifications made in the Arduino code

Code line	Output PWM Frequency	
	306 Hz	1835 Hz
82	delay (P0/3.06);	delay (P0/18.35);
84	delay ((100-P0)/3.06);	delay ((100-P0)/18.35);

```

1 #include <MegunoLink.h>
2 #include <Filter.h>
3 #include <LiquidCrystal.h>
4 int F0;
5 int P0;
6 int F1 = 0;
7 int P1 = 0;
8 int final = 250;
9 float F;
10 float P;
11 float E;
12 float modo;
13 int tipo = 2;
14 const int rs = 12, en = 11, d4 = 9, d5 = 8, d6 = 7, d7 = 6;
15 LiquidCrystal lcd(rs, en, d4, d5, d6, d7);
16 ExponentialFilter<long> ADCFilter(2, 0);
17 void setup() {

```

¹ Arduino code implemented and provided by Dr. J. A. G. Croce, sent by email to the author in 2018.

```
18  lcd.begin(16, 2);
19  lcd.print("Fonte Nova");
20  lcd.setCursor(0, 1);
21  lcd.print("11/2017");
22  delay(2000);
23  lcd.clear();
24 }
25 void loop() {
26  modo = analogRead(A2);
27  if (modo < 500) {
28    // Trecho para configuracao da frequencia e ciclo
29    noTone(2);
30    tipo = 1;
31    lcd.setCursor(0, 1);
32    lcd.print("<<<<Ajustando>>>");
33    for (int i = 0; i < final; i++) {
34      F += analogRead(A0);
35      P += analogRead(A1);
36      delay(1);
37    }
38    P /= final;
39    F /= final;
40    P0 = int(P);
41    F0 = int(F);
42    ADCFilter.Filter(F0);
43    ADCFilter.Filter(P0);
44    F0 = map(F0, 0, 1024, 3000, 8000);
45    F0 = int(F0 / 100);
46    F0 = 100 * F0;
47    P0 = map(P0, 0, 1024, 20, 200);
48    P0 = int(P0 / 2);
49    if (F0 != F1 || P0 != P1)
50    {
51      lcd.clear();
52      lcd.setCursor(0, 0);
53      lcd.print("F=");
54      lcd.setCursor(2, 0);
55      lcd.print(F0);
56      lcd.setCursor(6, 0);
57      lcd.print("Hz");
58      lcd.setCursor(10, 0);
59      lcd.print("C=");
```

```
60     lcd.setCursor(12, 0);
61     lcd.print(P0);
62     lcd.setCursor(15, 0);
63     lcd.print("%");
64     lcd.setCursor(0, 1);
65     lcd.print("<<<<Ajustando>>>");
66     F1 = F0;
67     P1 = P0;
68     delay(50);
69 } else {
70     F1 = F0;
71     P1 = P0;
72 }
73 } else {
74     // Trecho de acionamento da saida
75     if (tipo == 1) {
76         lcd.setCursor(0, 1);
77         lcd.print(">>>>Acionado<<<<");
78         tipo = 0;
79     } else if (tipo == 0) {
80         if (P0 < 99) {
81             tone(2, F0);
82             delay(P0);
83             noTone(2);
84             delay(100 - P0);
85         } else {
86             tone(2, F0);
87         }
88     } else {
89         lcd.setCursor(0, 0);
90         lcd.print(" Configurar ... ");
91     }
92 }
93 }
```