**UNIVERSITY OF SÃO PAULO
SÃO CARLOS SCHOOL OF ENGINEERING**

Daniel Acevedo Giraldo

**Experimental Aeroacoustic and Aerodynamic Analysis of
a Large-Scale Flap Side-Edge Model**

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

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**Análise Experimental Aeroacústica e Aerodinâmica de
um Modelo de Ponta de Flap de Grande Escala**

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**Experimental Aeroacoustic and Aerodynamic Analysis of
a Large-Scale Flap Side-Edge Model**

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School of Engineering - University of São
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gineering.

Concentration area: Aircraft

Supervisor: Prof. PhD. Fernando Martini
Catalano

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**São Carlos
2019**

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Daniel Acevedo Giraldo

**Análise Experimental Aeroacústica e Aerodinâmica de
um Modelo de Ponta de Flap de Grande Escala**

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Área de concentração: Aeronaves

Orientador: Prof. Dr. Fernando Martini Catalano

ESTE EXEMPLAR TRATA-SE DA VERSÃO CORRIGIDA. A VERSÃO ORIGINAL ENCONTRA-SE DISPONÍVEL JUNTO AO DEPARTAMENTO DE ENGENHARIA MECÂNICA DA EESC-USP.

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To my parents, Claudia and Nicolas, who have always trusted and believed in me.

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“Whatever your goal is you will never succeed unless you let go of your fears and fly.”

Richard Branson (1950)

ABSTRACT

ACEVEDO, G. D. **Experimental Aeroacoustic and Aerodynamic Analysis of a Large-Scale Flap Side-Edge Model**. 2019. 142p. Dissertation (Master of Science) - São Carlos School of Engineering, University of São Paulo, São Carlos, 2019.

The first bypass turbofan engines came into operation in the early 1970's. The need for reductions in the fuel consumption affected aircraft noise positively through reductions in the jet noise. Over the past decades, the bypass ratio of turbofan engines has continuously increased and, as a result, aircraft engine noise has decreased to a level comparable to the noise originated from the turbulent flow around the airframe for take-off and landing conditions. Although aircraft have become quieter, the number of individuals affected by the aviation growth is likely to increase. Airframe noise has been currently identified as the ultimate aircraft noise barrier and many efforts devoted to its reductions have focused specifically on landing gears and high-lift devices, which are the most relevant noise contributors. Some devices have been designed to reduce flap noise, however, not all of them have been successfully tested in a detailed large-scale flap model due to their difficult implementation in real flap side-edges. This research investigates the relationship between the parameters of a large-scale flap model at 1.50×10^6 Reynolds number and the physics responsible for flap side-edge noise generation, one of the most dominant sources of the airframe noise. Experimental tests were conducted in a wind-tunnel and flow-field measurements were taken by a multi-hole pitot probe and an aerodynamic balance and complemented by phased microphone array techniques towards a deeper understanding of flap side-edge noise sources and their correlations to unsteady vorticity fluctuations. Conventional beamforming and CLEAN-SC and DAMAS deconvolution methodologies provided far-field acoustic spectra estimations and noise source mapping. The model used for the tests consists of an unswept isolated flap element with representative tip details present in conventional medium-range transport aircraft. The instrumentation includes 106 steady pressure taps distributed chord-wise and span-wise and a sand trip tape to transition the laminar boundary layer. Different side-edge devices were assessed towards airframe noise reductions. A perforated side-edge treatment was also applied to the flap side-edge. Results of aerodynamic and aeroacoustic tests conducted in the LAE-1 closed circuit wind tunnel with a closed test section at the São Carlos School of Engineering - University of São Paulo (EESC-USP) at up to 40 *m/s* flow speeds provided specific information on the aeroacoustic and aerodynamic characterization of the dominant acoustic source mechanisms of the flap model.

Keywords: Aircraft noise. Airframe noise. Flap side-edge noise. Experimental aeroacoustics. Experimental aerodynamics. Beamforming techniques.

RESUMO

ACEVEDO, G. D. **Análise Experimental Aeroacústica e Aerodinâmica de um Modelo de Ponta de Flap de Grande Escala.** 2019. 142p. Dissertação (Mestrado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2019.

Os primeiros motores turbofan com razão de desvio entraram em operação no início dos anos 70. A necessidade de reduções no consumo de combustível afetou positivamente o ruído das aeronaves através de reduções no ruído do jato. Nas últimas décadas, a razão de desvio de motores turbofan aumentou continuamente e, como resultado, o ruído do motor da aeronave diminuiu para um nível comparável ao ruído originado do fluxo turbulento ao redor do *airframe* para as condições de decolagem e pouso. Embora as aeronaves tenham-se tornado mais silenciosas, é provável que o número de indivíduos afetados pelo crescimento da aviação aumente. Atualmente, o ruído de *airframe* tem sido identificado como a barreira máxima de ruído para aeronaves e muitos esforços dedicados à sua redução se concentraram especificamente no tren de pouso e dispositivos de alta sustentação, que são os contribuidores de ruído mais relevantes. Alguns dispositivos foram projetados para reduzir o ruído do *flap*, no entanto, nem todos deles foram testados com sucesso em um modelo detalhado de *flap* de grande escala, devido a sua difícil implementação nas bordas laterais do *flap* real. Esta pesquisa investiga a relação entre os parâmetros de um modelo de *flap* de grande escala com número de *Reynolds* de 1.50×10^6 e a física responsável pela geração de ruído na borda lateral do *flap*, uma das fontes mais dominantes do ruído de *airframe*. Testes experimentais foram realizados em um túnel de vento e as medidas do escoamento foram tomadas por uma sonda pitot de múltiplos furos e uma balança aerodinâmica e complementadas por técnicas de antenas de microfones para um entendimento mais profundo das fontes de ruído da ponta do *flap* e suas correlações com flutuações instáveis de vorticidade. O *beamforming* convencional e as metodologias de deconvolução CLEAN-SC e DAMAS forneceram estimativas de espectros acústicos de campo distante e mapeamento de fontes de ruído. O modelo usado para os testes consiste em um elemento de *flap* isolado, sem enfileiramento, com detalhes de ponta representativos presentes em aeronaves convencionais de transporte de médio alcance. A instrumentação inclui 106 tomadas de pressão estacionárias distribuídas na corda e na envergadura e um trip de fita de areia para fazer a transição da camada limite laminar. Diferentes dispositivos de borda lateral foram avaliados em relação às reduções de ruído de *airframe*. Um tratamento perfurado de borda lateral também foi aplicado à borda lateral do *flap*. Os resultados dos testes aerodinâmicos e aeroacústicos realizados no túnel de vento de circuito fechado LAE-1, com seção de provas fechada na Escola de Engenharia de São Carlos - Universidade de São Paulo (EESC-USP) com velocidade de fluxo de até 40 m/s

forneceram informações específicas sobre a caracterização aeroacústica e aerodinâmica dos mecanismos dominantes de fonte acústica do modelo de *flap*.

Palavras-chave: Ruído de aeronave. Ruído de *airframe*. Ruído de ponta de *flap*. Aeroacústica experimental. Aerodinâmica experimental. Técnicas de *Beamforming*.

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LIST OF ABBREVIATIONS AND ACRONYMS

AIAA	American Institute of Aeronautics and Astronautics
ANOPP	Aircraft Noise Prediction Program
ASCOT	Advanced Concepts to Test
AST	Advance Subsonic Technology
AWB	Acoustics Wind-tunnel Braunschweig
DBD	Dielectric Barrier Discharge
CAA	Computational Aeroacoustic
CAD	Computer Aided Design
CBF	Conventional BeamForming
CEAS	Aeroacoustics Conference
CFD	Computational Fluid Dynamics
CMT	Continuous Moldline Technology
CML	Continuous Moldline Link
CLEAN-SC	CLEAN based on Spatial Source Coherence
CSM	Cross Spectral Matrix
CTA	Constant Temperature Anemometry
DAMAS	Deconvolution Approach for the Mapping of Acoustic Sources
DLR	German Aerospace Center
DNW	German-Dutch Wind Tunnels
EESC	São Carlos School of Engineering
EASA	European Aviation Safety Agency
ECAC	European Civil Aviation Conference
EPM	Effective Perceived Noise
FAA	Federal Aviation Administration

FACT	Futuristic Airframe Concepts and Technologies
GDP	Gross Domestic Product
HBM	Hottinger Baldwin Messtechnik
HDF5	Hierarchical Data Format
HFA	Hot-Film Anemometry
HLD	High-Lift Devices
HWA	Hot-Wire Anemometry
ICAO	International Civil Aviation Organization
IEPE	Integrated Electronic Piezo-Electric
JAXA	Japan Aerospace Exploration Agency
LAE	Laboratory of Aerodynamics
LaRC	Langley Research Center
LE	Leading-Edge
LLF	Large Low-speed Facility
MTOM	Maximum Take-Off Mass
NASA	National Aeronautics and Space Administration
NC	Noise Calibrator
NI	National Instruments
NRL	National Aerospace Laboratory
OASLP	Filtered Overall Sound Pressure Level
PIV	Particle Image Velocimetry
PS	Pressure Side
PSD	Power Spectral Density
PRLE	Protruding Rounded Lower-Edge
PXI	PCI eXtensions for Instrumentation
QAT	Quiet Aircraft Technology

ROI	Region of Interest
SARPs	Standards and Recommended Practices
SNR	Signal to Noise Ratio
SOR	Start of Roll
SPL	Sound Pressure Level
TE	Trailing-Edge
TEDS	Transducer Electrical DataSheet
U.S.	United States
USP	University of São Paulo
VALIANT	Validation and Improvement of Airframe Noise Prediction Tools
ZOC	Zero, Operate and Calibrate

LIST OF SYMBOLS

α	Angle of attack [$^{\circ}$]
a	Speed of sound [m/s]
AR	Aspect ratio ($= b/c$)[-]
b	Span [m]
c	Chord [m]
C_D	Drag coefficient ($= D/qbc$)[-]
$C_D \min$	Minimum Drag coefficient [-]
C_L	Lift coefficient ($= L/qbc$)[-]
$C_L \max$	Maximum lift coefficient [-]
C_M	Moment coefficient ($= M/qbc^2$)[-]
C_P	Pressure coefficient ($= (P_s - P)/q$)[-]
C_1	Specific constant for air [$1.458 \cdot 10^{-6} kg/(m \cdot s \cdot K^{1/2})$]
C_2	Specific constant for air [$110.4 \cdot K$]
ΔdB	Noise reduction [dB]
Δf	Frequency band [Hz]
D	Drag force [N]
η_k	Non-dimensional height in boundary layer based on roughness height [-]
e	Efficiency factor [-]
f	Frequency [Hz]
γ	Ratio between specific heat at constant pressure and constant volume [1.4]
K	Roughness Height of the trip [m]
L	Lift force [N]

L_p	Level of the pressure [dB]
μ	Dynamic viscosity [$Pa.s$]
m	Slope [dB/dec]
M	Mach number ($= U/a$) $[-]$
$M_{0.25c}$	Moment at $0.25c$ [Nm]
M_d	Molar mass of dry air [$0.028964\ kg/mol$]
M_v	Molar mass of water vapor [$0.018016\ kg/mol$]
ν	Kinematic viscosity [m^2/s]
ν_k	Kinematic viscosity in the boundary layer of the trip [m^2/s]
N	Mach scale factor $[-]$
N_k	Thickness of the trip wire [m]
N_m	Number of microphones of the array $[-]$
ϕ	Relative humidity [%]
P	Atmospheric pressure [Pa]
P_d	Partial pressure of dry air [Pa]
P_s	Static pressure [Pa]
P_{sat}	Saturation pressure [Pa]
P_{ref}	Reference pressure [$20^{-6}\ Pa$]
P_v	Partial pressure of water vapor [Pa]
q	Dynamic pressure [Pa]
ρ	Air density [kg/m^3]
ρ_h	Humid air density [kg/m^3]
R_d	Specific gas constant for dry air [$287.058\ J/(kg.K)$]
R_t	Specific gas constant for water vapor [$461.495\ J/(kg.K)$]
R_k	Roughness Reynolds number based on trip height $[-]$
R_x	Roughness Reynolds number based on the chordwise location of the roughness $[-]$

Re	Reynolds number based on the flap chord length and free-stream velocity ($=Uc/\nu$) $[-]$
S	Flap area $[m^2]$
St	Strouhal number based on the flap chord length and free-stream velocity ($=fc/U$) $[-]$
T	Temperature $[^{\circ}C]$
U	Free stream velocity ($= (2q/\rho_h)^{1/2}$) $[m/s]$
U_k	Velocity in the boundary layer of the trip $[m/s]$
V^*	Non-dimensional velocity magnitude ($= V/U$) $[-]$
ω^*	Non-dimensional vorticity ($= \omega/U$) $[-]$
u, v, w	Cartesian component of velocity in X, Y and Z direction $[m/s]$
u^*, v^*, w^*	Non-dimensional cartesian component of velocity in X, Y and Z directions ($= u/U, = v/U, = w/U$) $[-]$
U_x, U_y, U_z	Cartesian component of velocity in X,Y and Z direction $[m/s]$
x	Surface distance measured streamwise from the leading-edge to the roughness station $[m]$
X, Y, Z	Cartesian coordinates, X positive downstream, Y positive up, Z positive to flap suction side $[-]$

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1 INTRODUCTION

Civil aviation has become one of the most important parts of the worldwide transport industry over the past decades. Passenger air traffic continues to grow and shows no signs of slowing down. Moreover, cities tend to expand near airports and at least 21 million individuals are affected by aircraft noise and have developed health problems. The aviation industry represents 3.6% of global Gross Domestic Product (GDP) and the recent air transportation growth and its consequent important environmental impacts have been identified as a socially relevant issue. Take-off and landing procedures result in strong aircraft noise produced mainly by engines and airframe. Noise reduction has become an important concern for civil aircraft manufacturers due to the noise restrictions to aircraft certification and operations imposed by authorities. Therefore, the civil aviation industry has developed means of reducing aircraft noise, optimizing operational procedures and improving land planning and use around airports.

Airframe noise became more significant after the decrease in the noise of the propulsion system. Its primary components are high-lift devices and landing gear, each with a specific noise peak frequency. Sharp edges at the flap side-edge generate perturbations in the air moving through the airframe which converted into noise. In the late 1970's, experimental studies revealed a source of a dominant airframe noise was associated with the side-edges of deployed wing flaps and many flap modifications for noise reductions have been investigated. Although a dominant vortex resulting from a dual vortex system of the flap side-edge has been identified as the main source of airframe noise, an aerodynamic and aeroacoustic comprehensive technological evaluation of the different real-scale devices is still a hard task.

This investigation focuses on noise reduction associated with the flow-field around a detailed flap side-edge. The analyses provide a much deeper understanding of the mechanisms responsible for the flap noise generation on the subject of large-scale flap side-edge noise for the correct quantification of the noise parameters modeled in Reynolds number at take-off and landing conditions. Experimental aeroacoustic and aerodynamic measurements were conducted by a large-scale flap model, with representative tip details of a conventional commercial aircraft for a better understanding of the relationship between airframe noise and the phenomena of flow-field around flap side-edge. The relative contribution of each noise source to the overall airframe noise (at first with baseline flap model configuration and then the flap model with different flap side-edge geometries) is shown in the experimental measurement results of phased array microphones, static pressure taps, aerodynamic forces and flow and wake mapping. The experimental techniques were applied in a closed circuit wind tunnel at different deflection angles and Reynolds number

based on the stowed chord length of the model of 1.50×10^6 , toward the understanding of the physics behind the flap side-edge noise.

1.1 Objectives of the research

This research was focused on the understanding of noise generation mechanisms associated with the flow-field around a flap side-edge and their reduction through experimental wind tunnel tests. A variety of experimental techniques were employed towards the understanding of the physics responsible for noise production mechanisms and noise reduction devices at the flap side-edge.

The model used in the tests in the LAE-1 wind tunnel of the São Carlos School of Engineering - University of São Paulo (EESC-USP) consists of a 3D flap representative of a conventional commercial aircraft developed in the scope of the EMBRAER Silence Aircraft Project. Experiments were conducted on a baseline case and three main different flap side-edge tips and with two perforated side-edge treatments. Measurements taken included microphones, surface pressure, aerodynamic forces and flow-field characterization. Oil flow was also used for on-surface flow visualization. Aeroacoustic measurements were performed with a microphone array and the results were processed according to frequency domain beamforming techniques (conventional Beamforming and CLEAN-SC and DAMAS deconvolution methodologies) for acoustic source localization and level analysis. Aerodynamic characteristics were measured by steady pressure transducers in both chord-wise and span-wise directions, an external three-axis balance and an L-shape 7-hole pitot probe from AeroProbe®.

1.2 Structure of the dissertation

This dissertation is divided into four main sections. Chapter 2 provides a review of the relevant literature in the field, including aircraft and airframe noise principles and flap side-edge noise fundamentals.

The experimental set-up and analyses and procedures are detailed and discussed in Chapters 3 and 4, respectively. The former describes the design of the flap model and the the wind tunnel facility, as well as the test conditions and aeroacoustic and aerodynamic experimental techniques applied. Chapter 4 addresses the nomenclature used, data post-processing and instrumentation calibration.

Chapter 5 reports the results and discussions for the experiments performed with six different flap side-edges tips and describes the aeroacoustic and aerodynamic effect of application of a perforated side-edge to two configurations.

Finally, Chapter 6 provides both aeroacoustic and aerodynamic experimental conclusions and recommendations.

2 STATE-OF-THE-ART

Flap side-edge noise results from a complex flow-field present at the flap tip of the aircraft wing. This chapter provides a literature survey on aerodynamics and aeroacoustics of flap side-edge. The problem of flap tip noise is placed in a context of the overall aircraft noise toward the understanding of the societal and environmental relevance of the topic. [Section 2.1](#) reviews the aircraft noise principles, noise standard limits and noise reduction goals. [Section 2.2](#) describes the main airframe noise sources and their relevance and contributions to the overall aircraft noise. [Section 2.3](#) discusses the fundamentals of flap side-edge noise, which include noise generation mechanisms proposed by several authors, noise prediction models, possible noise reduction strategies for flap side-edge by active and passive technologies, and the main aeroacoustic and aerodynamic experimental research conducted in wind tunnel facilities.

2.1 Aircraft noise

Aircraft noise is defined as the noise perceived by an individual on the ground. The total noise is the result of the sound radiated by several sources related to an aircraft. The contribution of each source to the overall aircraft noise varies in function of the flight phase. The aircraft noise refers mainly to propulsion system noise and airframe noise ([SMITH, 1989](#)), also known as "non-propulsive noise of an aircraft in flight" ([CRIGHTON, 1991](#)). In the 1970's, aircraft noise became a subject of exhaustive research interest after the initial studies of ultra-quiet military surveillance aircraft conducted in the late 1960's. It has increased due to the growth of aircraft operations and expansion of airport facilities close to populated areas. Such noise produced by aircraft components during approach has been controlled since the 1970's by the International Civil Aviation Organization (ICAO), which has monitored and updated noise standard limits for aircraft in Standards and Recommended Practices (SARPs) contained in Annex 16 to ensure aviation regulation ([ICAO, 2013](#)).

According to [ICAO \(2011\)](#), an airplane cannot exceed the Effective Perceived Noise (EPNdB) in acoustic certification tests determined at three reference points of an airport ([Figure 1](#)), namely approach, under the descent path 2000 *m* before the landing threshold, lateral (or sideline), where noise is louder on a line 450 *m* to the side of the initial climb after lift-off, and flyover, under the departure climb path, 6500 *m* from the Start Of Roll (SOR) ([ICAO, 2011](#)).

Figure 1: Noise certification reference points

Reference: [European Civil Aviation Conference - ECAC \(2005a, 2005b\)](#)

Moreover, [ICAO \(2016\)](#) established:

Aircraft noise is the most significant cause of adverse community reaction related to the operation and expansion of airports. This is expected to remain the case in most regions of the world for the foreseeable future. Limiting or reducing the number of people affected by significant aircraft noise is therefore one of ICAO's main priorities and one of the organization's key environmental goals. The main overarching ICAO policy on aircraft noise, which contains details on all the elements that can be employed to achieve noise reductions, is the Balanced Approach to Aircraft Noise Management

ICAO noise standards became applicable in 1973 through Chapter 2 (noise standard contained in Annex 16, Volume I), which introduced noise limits of an aircraft as a direct function of Maximum Take-Off Mass (MTOM) for identifying the one that produced the loudest noise. Chapter 3 (noise standard contained in Annex 16, Volume I) is more restrictive and was written in 1977, when higher bypass ratio jet engines began to be used and required strict noise regulations. Chapter 4 (noise standard contained in Annex 16, Volume I) was applicable in 2006. New acoustic technologies have been adopted by aircraft and engine designs and led to an increase in the number of regulations. Finally, the new Chapter 14 will be applicable between 2017 and 2023 with 7 EPNdB noise reduction related to a previous chapter, as shown in [Figure 2](#).

Figure 2: Progression of the ICAO noise standard

Reference: [Dickson \(2015\)](#)

As stated by [Smith \(1989\)](#), airframe noise is the ultimate aircraft noise barrier. In 2020 and 2025, respectively, U.S. ([DOBRZYNSKI, 2010](#)) and European ([ARGÜELLES et al., 2001](#); [EUROPEAN AVIATION SAFETY AGENCY - EASA, 2012, 2016](#)) governments expect to achieve 10 and 20 *dB* aircraft noise reductions relative to the year 2000 technology.

[Figure 3](#) shows the nuisance aircraft-noise footprint around airports containing noise-reduction goals of the National Aeronautics and Space Administration (NASA).

Figure 3: NASA reduction goals within the boundaries of an airport until 2025

Reference: [NASA \(2010a\)](#)

The specific goal of NASA is the development of a technology for noise reductions of 32 *dB* by 2020/2025, 42 *dB* by 2025/2030, and 52 *dB* by 2030/2035, as shown in [Table 1](#) ([NASA, 2010b](#)). Such reductions are related to current Federal Aviation Administration

(FAA) standards for aircraft in service relative to the year 1980 aircraft noise. The goals have been recently proven achievable through a NASA project focused on more environmental-friendly aviation ([NASA, 2010a](#)).

Table 1: NASA reduction goals

Area to improve	NASA Reduction Goals		
	Aircraft entering Service in 2020-2025	Aircraft entering Service in 2025-2030	Aircraft entering Service in 2030-2035
Noise (Cumulative margin relative to ICAO 8.4.2 FAA stage 4 noise limit)	-32dB	-42dB	-52dB

Reference: modified from [NASA \(2010b\)](#)

The noise produced by aircraft in airports has been studied for decades on different national and international research programmes and is still one of the main focuses of many research efforts towards the development of new reduction technologies to meet certification standards of the aircraft of the future ([DICKSON, 2015](#)).

Airframe noise research began as a consequence of noise reduction in propulsion systems resulting from the increase in the high-bypass ratio engines in 1970's, which made airframe noise a predominant component of the overall aircraft noise. From 1980 to 1990, the interest in airframe noise decreased due to the first fuel crisis. Intense airframe noise research began in the 1990's with NASA programs, as Advance Subsonic Technology (AST) and Quiet Aircraft Technology (QAT) ([CHOUDHARI et al., 2002](#); [MACARAEG, 1998](#)) and since then, it has been a topic of interest in aviation ([DOBRZYNSKI, 2008](#)). Many experimental, analytical, and numerical investigations have been conducted towards the understanding of the flow dynamics around aircraft and their noise sources. NASA has also developed new research programs on airframe noise under the Advanced Concepts to Test (ASCOT) and Futuristic Airframe Concepts and Technologies (FACT). All of them involve partners in both industry and academia, as NASA Langley Research Center (LaRC), for investigating and determining fundamental noise source mechanisms by relating fundamental fluid mechanics to sound generation mechanisms ([MACARAEG, 1998](#)).

In recent years, airports and regulatory authorities have employed sound level contour maps as a noise-prediction tool through a combination of sound level measurements and appropriate sound-mapping software. Noise, defined as “unwanted sound”, consists of fluctuations in pressure, which is a force per unit area. [Equation 2.1](#) shows the Sound Pressure Level (SPL) described by [ICAO \(2016\)](#).

$$L_p = SPL = 20 \log_{10}(P/P_{ref}) \quad (2.1)$$

2.2 Airframe noise sources

[Dobrzynski \(2008\)](#) stated airframe noise is generated from the interaction of turbulent flows with solid bodies. According to [Crighton \(1991\)](#), the following five main mechanisms have been recognized since 1970's due to their important contribution to airframe noise:

- a) wing trailing-edge scattering of boundary-layer turbulent kinetic energy into acoustic energy;
- b) vortex shedding from slat/main-body trailing-edges and the possible gap tone excitation through nonlinear coupling in the slat/flap coves;
- c) flow unsteadiness in the recirculation bubble behind the slat leading-edge;
- d) roll-up vortex at the flap side-edge; and
- e) landing-gear multi-scale vortex dynamics and the consequent multi-frequency unsteady force applied to the gear components.

[Figures 4 and 5](#) show the main sources of airframe noise in take-off and landing phases, respectively, for a twin-engine long-range transport aircraft. Engine noise is the major contributor to the overall aircraft noise during take-off, since the engines are set to their maximum power to provide the necessary thrust. The contribution of the airframe noise is more significant during the approach operation, once it becomes equally important as engine noise ([CHOW; MAU; REMY, 2002](#)), since the aircraft demands less thrust and the generation of engine noise is reduced. Both High-Lift Devices (HDL), namely flap and slat and landing gear are the main sources of overall aircraft noise only during approach and take-off, since all of them are retracted in the cruise phase ([AIRBUS, 2007](#)).

Figure 4: Aircraft noise sources

Reference: modified from [Morgan and Hardin \(1974, 1975\)](#)

Figure 5: Noise sources breakdown

Reference: modified from Airbus (2007)

The current major detailed contributions to airframe noise for commercial aircraft are parasitic noise sources, landing gears, high-lift devices (slotted slats, flap and slat side-edges, flap and slat tracks, spoilers) and component interaction noise sources, e.g., gear-wake/flap interaction (CHOW; LEMPEREUR; MAU, 1999; DOBRZYNSKI, 2010; HERR, 2012). Less important airframe noise sources are wing tip noise, noise from “infinitely extended” surfaces (boundary layer noise including roughness effects and noise from surface vibration), free wake turbulence and tonal vortex shedding noise from smooth circular landing gear struts (DOBRZYNSKI, 2008).

2.2.1 Parasitic noise sources

Defined as a noise produced by non aerodynamic elements in landing gear (struts, joints and hollow pins) and wings (cutouts in the wing leading-edge and cavities in flap side-edge), parasitic noise exhibits both tonal and broadband characteristics and significantly contributes to the overall airframe noise signature.

2.2.2 Landing gears

Since 1990's, landing gears have been recognized as one of the main contributors to airframe noise due to their noise levels in the 0.5 to 3 kHz range, which corresponds to the most sensitive range of human noise perception. The landing gear structure noise is produced by the interaction of turbulent wake flows with downstream-located gear elements and the turbulent flow separation of different bodies of each individual gear

element. The noise produced displays essentially broadband characteristics.

2.2.3 High-lift devices

- a) Slotted slats: according to [Khorrami, Singer and Berkman \(2002\)](#) and [König et al. \(2010\)](#), the broadband noise mechanism component of slat noise at lower frequencies is associated with the interaction between unsteady vorticity structures in the slat-cove region and adjacent features of the high-lift geometry;
- b) Flap and slat side-edges: some of the most effective sources of airframe noise, according to the two noise generation mechanisms described by [Rossignol \(2013\)](#). The former is a direct interaction between the shear layer unsteadiness and the sharp edge, and the second is the induction of vortex unsteadiness interacting with the surfaces and edges ([CASALINO et al., 2008](#));
- c) Flap and slat tracks: differently from flaps and Slats, the airframe noise generated from tracks has not been precisely quantified, since slat and flap track geometries have never been reproduced in scale model aircraft accurately. However, an initial comparative testing of different slat tracks proved track noise is an issue for future low airframe noise ([DOBRZYNSKI, 2010](#)); and
- d) Spoilers: although spoilers source noise mechanisms are not known in detail, they are sources of low frequency noise. Spoiler deflection directly affects wing circulation and generates slat noise ([DOBRZYNSKI, 2008](#)).

2.2.4 Gear-wake/flap interaction

Research has indicated the noise from deployed landing gear can exceed the overall flap leading-edge noise downstream. The gear, rather than the cavity, has been one of the main noise contributors to the turbulent wake in flap ([HUTCHESON; STEAD; PLASSMAN, 2016](#); [OERLEMANS; POTT-POLLENKE, 2004](#)).

[Lighthill \(1952\)](#) described three different mechanism of conversion of energy from the kinetic energy of fluctuating shearing motions into the acoustic energy of fluctuating longitudinal motions. The flap side-edge noise is typically represented as follows:

- a) by forcing the mass in a fixed region of space to fluctuate, e.g., a loudspeaker diaphragm embedded in a very large baffle;
- b) by forcing the momentum in a fixed region of space to fluctuate, or forcing the rates of mass flux across fixed surfaces to vary; e.g., a solid object vibration after being struck; and
- c) by forcing the rates of momentum flux across fixed surfaces to vary, e.g., sound generated aerodynamically with no motion of solid boundaries.

2.3 Flap side-edge noise

The flap side-edge noise mechanisms consist of the pressure differential between the upper and lower surfaces produces an oscillating vortical system (Figure 6), which results in a strong broadband noise. Such a system is characterized by the generation of two separate vortices in the upstream region of the flap, i.e., one at the upper flap side contour and the other at the lower flap side contour (REICHENBERGER, 2016). As stated by Molin, Roger and Barre (2003), in general, any vortical pattern in a flow generates sound as soon as its inertia has been modified, since the corresponding change in the pressure gradients also induces density fluctuations that propagate as sound. At commonly subsonic Mach numbers, sound is generated when convected vortical patterns interact with solid surfaces.

Figure 6: Illustration of the vortical structure

Reference: Koop et al. (2002)

2.3.1 Noise-generation mechanisms

Khorrani and Singer (1999) analyzed the possible sources of local flow unsteadiness to identify noise sources. Based on the description of the flow-field, the authors proposed the following five sources:

- a) large-scale flow fluctuations supported by the free-shear layer emanating from the flap bottom edge and spanning the entire flap chord;
- b) large-scale flow fluctuations supported by the post-merged vortex downstream the flap mid-chord region;
- c) convection of a turbulent boundary layer over the sharp edges at the flap side-edge, which gives rise to scattering and broadband sound radiation;
- d) vortex merging; and
- e) vortex breakdown.

The first two are responsible for most audible noise generation, whereas vortex merging and vortex breakdown are low-frequency phenomena not as important as the other items in the audible spectrum. The problem of turbulent boundary layer sharp-edges, e.g., side/trailing-edge noise, received plenty of attention in the past and its sound radiation laws for scaling from near- to far-field are well known (STORMS et al., 1998).

Figure 7 shows a schematic representation of the envisioned noise-generation mechanisms associated with the first two local flow-field features, namely instabilities in the shear layer and vortex, designed by Khorrami and Singer (1999). Figure 7(a) illustrates the shear layer separated at the bottom flap side-edge that fed the vortex system for the mid-chord region, where the cylindrical shear layer is the dominant source. The curved shear layer is present along the entire flap chord and supports large-scale flow perturbations. The flow-field, excited by these perturbations, involves two possible noise-producing scenarios. First, the shear layer fluctuations migrate to the outer part of the vortex by traveling to the vicinity of the sharp edges by the vortex velocity field. Then, they move towards the vortex interior and vortex modes are amplified when the frequencies of the fluctuations overlap the frequency range of unstable vortex modes. In both cases, the unsteady pressure flow-field near the flap sharp edges radiates sound. Figure 7(b) shows the noise generation mechanism created by the presence of the post-merged vortex located on the flap upper surface near the sharp edge. Perturbations within an appropriate frequency range results in strong localized pressure perturbations in the vicinity of a sharp edge, where the unsteady pressure flow-field is an acoustic radiator (HOWE, 1982).

Figure 7: Envisioned noise-generation mechanism

Reference: modified from Khorrami and Singer (1999)

Choudhari and Khorrami (2003) listed four noise-producing features near a flap side-edge, namely:

- a) free shear layers and their roll-up;
- b) formation of multiple vortices;
- c) vortex merging-scattering and broadband sound radiation; and
- d) vortex bursting when the flap deflection is sufficiently large.

Choudhari et al. (2002) provided a schematic overview of the acoustic spectrum (Figure 8) resulting from the previous four noise-generating mechanisms. Figure 9 shows the total spectral shape function as the summation of the low- and high-frequency components for a flap side-edge (GUO, 2011).

Figure 8: Schematic acoustic spectra of turbulent flap side-edge noise sources

Reference: Choudhari et al. (2002)

Figure 9: Spectral shape functions for low and high-frequency components

Reference: Guo (2011)

According to Drobietz and Borchers (2006) and Reichenberger (2016), the flap local flow-field comprises the following noise-generation mechanisms (Figure 10):

- a) Trailing-edge noise and flow separation at the tip edges (I). The turbulent boundary layer on the pressure side of the flap moves across the lower flap side-edge. This mechanism is present in the entire flap chord region (I.a). The turbulent boundary layer on the side of the flap moves across and separates at the upper flap side-edge (I.b);
- b) Fluctuations in the side-edge vortex pressure interacting with the flap side surface and upper side-edge. The vortex is fed by shear instabilities from lower side-edge. This mechanism is present in the mid-chord region (II);
- c) Merging of the two vortices (III); and
- d) Fluctuations on the merged vortex pressure interacting with the flap suction and the upper side-edge (IV). The merged vortex moves upwards. This mechanism is limited to a small region slightly downstream the merging location, and a jet-like noise generation in the accelerated vortex core may play an important

role (IV.a). The vortex breakdown is a noise source (IV.b). The merged vortex remains close to the upper surface and interacts with the flap suction side and the upper side-edge (IV.c). The merged vortex passes the trailing-edge and interacts with the trailing-edge corner (IV.d).

Figure 10: Scheme of the flap side-edge local flow-field

Reference: [Drobietz and Borchers \(2006\)](#)

Flap side-edge noise is considered a broadband component. The post-merged vortex interacting with the flap suction side and the trailing-edge and the shear layer originating at the lower ridge of the flap tip produce most of the audible noise. The unstable merged vortex generates noise in low to mid frequencies, whereas the mid- to high-frequency noise is radiated by turbulent shear layer instabilities.

2.3.2 Prediction models

Efforts have been devoted towards the production of different aircraft noise prediction tools. Aircraft designers are focused on reducing noise sources, which requires the development of prediction models to provide detailed information on noise. Civil aviation operators are interested in accumulating enough noise metrics for operation near airports to ensure compliance with regulations. In general, researchers have focused on improvements in airframe noise prediction methods that include numerical methods, analytical relations, and semi-empirical correlations. Such studies provide a better understanding of noise source mechanisms for new techniques on experimental noise measurements and numerical simulations. Aircraft noise prediction models can be classified into two categories, namely theoretical methods and best practice methods. The former relies on the form of the physical model of noise production and propagation engineering (e.g., finite element

methods and computational fluid dynamics), whereas the latter relies almost exclusively on measurement databases ([FILIPPONE, 2014](#)).

In the early 1970's, FAA and NASA started to conduct research on the theoretical aircraft noise prediction model with the development of the ANOPP (Aircraft Noise Prediction Program) code. This computational program integrated noise generations and propagation mechanisms of the fan, compressor, jet, wing and landing gear with the aircraft flight dynamics ([RANEY, 1976](#)). ANOPP2 has been updated to ensure improvement and predictive accuracy; it uses higher fidelity of computational methods ([LOPES; BURLEY, 2011](#)) and source and propagation models are studied independently.

[Fink \(1977\)](#) developed the first empirical aircraft noise prediction model based on experimental flight data from various sources of different aircraft. The statistical analysis of such data correlates airframe noise levels with global geometry parameters of a high-lift system. Since the physics of correlation between acoustic intensity and aircraft components design is not considered a simple treatment, alternative strategies for noise prediction must be employed in the early design phase of components. High-fidelity methods, such as Computational Fluid Dynamics (CFD) and Computational Aeroacoustic (CAA) analysis enable the creation of more efficient and accurate components. Moreover, efforts have been devoted towards overcoming the limitations of these methods on experimental acoustic analogies, i.e., experimental tests of single components and flight tests.

Relevant experimental aeroacoustic advances in airframe noise methods have been achieved by the German Aerospace Center (DLR) in both Large Low-speed Facility (DNW-LLF) closed test section and Anechoic Acoustics Wind-tunnel Braunschweig (AWB) through phased arrays and beamforming techniques that validate noise prediction and reduction methods ([DOBRZYNSKI et al., 2008](#); [ROSSIGNOL, 2010](#)).

2.3.3 Noise reduction technologies

Different flow control solutions have been proposed towards reductions in the flap side-edge noise. The flap side-edge modifications described in the literature alter the flow-field around the flap tip by either displacing the vortex away from the flap surface, or reducing lift loading in the flap side-edge region and its strength.

2.3.3.1 Passive control devices

- a) Flap-tip fences: a flap-tip Fence is a perpendicular side plate mounted at the flap side-edge ([Figure 11](#)). [Horne et al. \(1997\)](#) proposed the use of flap side-edge fences to increase the distance between the vortex system and the top surface of the flap. It eliminates the roll-up of the shear layer and locks the position of the side-edge vortex near the bottom edge to reduce the flap side-edge noise ([CHOUDHARI; KHORRAMI, 2003](#)). According to [Guo and Joshi \(2003\)](#), who

performed airframe noise tests using McDonnell Douglas DC-10 model, the exact mechanism by which noise is reduced by flap side-edge fences has not been fully understood and the amount of noise reduction does not increase linearly with the fence height. Although flap side-edge fences effectively reduce high-frequency noise, they increase the noise level at low frequencies, i.e., they are more effective for high frequencies, since they reduce the source strength by slowing down the local flow around the flap side-edge. [Ross and Storms \(1998\)](#) examined different tip fences (lower and higher) that extended approximately one flap thickness below/above the flap lower/higher surface. The reduction found was $3 - 4 \text{ dB}$ for frequencies between $2 - 11 \text{ kHz}$. [Guo \(2004\)](#) also discussed the effects of fences on side-edge cross flows through an analytical model based on vortex dynamics and observed fences reduced the flap noise by shifting the source spectra downward in frequency, because of the blockage effects.

Figure 11: Schematic cross-sectional view of vortex structures near the flap tip

Reference: modified from [Storms and Ross \(1996\)](#)

- b) Continuous Moldline Technology (CMT): CMT involves the use of a flexible panel also called Continuous Moldline Link (CML), which deforms towards completely eliminating the flap tip and providing a continuous surface ([Figure 12](#)). [Storms et al. \(2000\)](#) applied CMT at the flap tip of a wind tunnel model and compared it with a simplified wing with a half-span hinged flap. CMT induced an aerodynamic reduction that affected the overall lift, however, the flap side-edge noise source was reduced. According to [Hutcheson, Brooks and Humphreys Jr. \(2011\)](#), the noise from the CML region of the flap is 5 to 17 dB

lower than that from the side-edge region of a simple blunt side-edge, depending on the flap deflection and Mach number.

Figure 12: Continuous moldline link flap tip

Reference: modified from [Hutcheson, Brooks and Humphreys Jr. \(2011\)](#)

- c) Protruding Rounded Lower-Edge (PRLE): according to [Murayama et al. \(2017\)](#), the PRLE controls the generation and flow structure of vortices in the lower side of the flaps attaching the excessive turbulence on the flap side-edge with round-shaped protrusion under it. Additionally, the remaining upper side vortex that shifts away from the upper side-edge can be reduced by an interaction of PRLE with the flap side-edge. Such a noise-reduction device can reduce approximately 2 *dB* of the flap side-edge noise and requires no significant structural and geometric flap side-edge changes.

Figure 13: Scheme of the PRLE local flow-field

Reference: [Drobietz and Borchers \(2006\)](#)

- d) Porous treatment of the flap-tip region: [Chow, Mau and Remy \(2002\)](#) replaced part of the flap side-edge by a brush and an open cell porous edge ([Figure 14](#)) and achieved noise reduction. In a 1/11 scale A320 model, the combined effect of slat cove filler and porous flap side-edge on the far-field noise reduced over 2 *dB* of the noise at some angles. The porous treatment reduces 4 to 8 *dB* of the noise in a wide range of frequencies and incurs no loss of lift ([CHOUDHARI; KHORRAMI, 2003](#)). The brush effect on the flap side-edge reduces approximately 5 *dB* in comparison to the completely clean side-edge. [Choudhari and Khorrami \(2003\)](#) observed a transpiration effect through the porous segments. The treatment incites a weakening of the main side-edge vortex in the flap mid-chord region. Such an effect displaced the side and top vortices and the connecting shear layers away from the solid surfaces. [Catalano, Vanuchi and Correa \(2012\)](#) conducted an experimental investigation to determine the flap side-edge noise reduction testing a porous device (metallic perforated plate) and decreasing the vortex strength and the shear layer that fed the vortex, hence, its position in relation to the baseline model. According to [Drobietz and Borchers \(2006\)](#), a porous edge may exert the following influence on the noise source mechanisms: the steady leakage flow changes the mean local flow-field and the associated dual vortex system; the porous material acts as an acoustic absorber and a hydrodynamic absorber through the dissipation of turbulences; it changes solid wall impedance and reduces the surface radiation efficiency.

Figure 14: Porous flap tip for airframe noise reduction

Reference: modified from [Choudhari and Khorrami \(2003\)](#)

- e) Serrated trailing-edge corners, the so-called “noise weeder”: another technology created to reduce noise at the trailing corner of the flap side-edge is shown in [Figure 15](#). According to [Drobietz and Borchers \(2006\)](#), serrations on the flap

side trailing-edge significantly reduce the noise produced by the interaction of the merged vortex and the flap trailing-edge. However, the serration size and angle, covered trailing-edge proportion, depths of the material and the material resistance must be correctly selected. [Choudhari et al. \(2002\)](#) assured serration produces less than 0.5% change in lift and [Howe \(1991\)](#) also studied the behavior of serrations used to cover the full extended trailing-edge. However, the authors did not investigate the way the aerodynamic performance could be degraded.

Figure 15: Schematic view of serrated trailing-edge

Reference: [Drobietz and Borchers \(2006\)](#)

- f) Vortex generators for flap upper-side: Vortex Generators (VGs) are attached on the upper side of the flap and produce small-scale co-rotating vortices that reduce the flap side-edge vortex. In a recent investigation, the Japan Aerospace Exploration Agency (JAXA) used five VGs aligned in the span-wise direction on the upper surface of the flap near the leading-edge ([Figure 16](#)) to demonstrate the magnitude of the upper vortex is decreased by the interaction of vortices from VGs. These devices increase the pressure fluctuation level along the paths of small vortices generated by VGs and reduce the region of high-pressure fluctuation near the flap-tip derived from the upper vortex generated by the flap-tip ([MURAYAMA et al., 2017](#)). Although the noise reduction in the baseline configuration was approximately 1.5 dB, the increase in the height of VGs exerted a noise reduction effect on some frequency range.

Figure 16: Vortex generators for flap upper-side

Reference: modified from [Murayama et al. \(2017\)](#)

- g) Small vortex generators referred to as microtabs: according to [Choudhari et al. \(2002\)](#), microtabs are small trapezoidal devices ([Figure 17](#)) that move vortices away from their corners and increase the thickness of the resulting detached shear layer. According to the technique, they are positioned near the flap side-edge on the flap pressure surface close to the lower sharp edge to modify the shear layer and reduce instabilities. Their use significantly reduced noise from 7 to 40 kHz , however, they increased it between 40 and 50 kHz , probably due to fluctuations of the flow in the trailing-edge noise at the lower sharp edge.

Figure 17: Schematic view of a typical microtab local flow-field

Reference: [Drobietz and Borchers \(2006\)](#)

- h) Flat, flange, grit and round flap side-edge: [Brooks and Humphreys \(2003\)](#) conducted aeroacoustic tests to investigate the noise generation on flap side-edges through different treatments. The model used was mounted in an open-

jet facility designed for anechoic acoustic testing. The treatments applied (Figure 18) were a flat edge flap accompanied by edge modifications, a flange edge of $1/8$ in cavity depth and 0.05 in thickness, a round-edge attachment, i.e., a half-circle cross-section shape that matches the airfoil contour, and a grit for investigations of the effect of surface roughness on the flap edge noise. All flap side-edge geometries are currently used in aircraft. The spectra and directivity for each configuration were scaled for flow speed, surface roughness, and flap angles through a simplified boundary-layer calculation method. Some treatments reduced noise for low and high frequencies, whereas others increased high-frequency noise.

Figure 18: Sketch of different flap side-edge treatments

Reference: [Brooks and Humphreys \(2003\)](#)

2.3.3.2 Active control techniques

- a) Active flow control: According to [Koop et al. \(2002\)](#) and [Koop, Ehrenfried and Dillmann \(2004\)](#), active flow control consists in the continuous blow of air through orifices into the vortical structure for neutralizing the vortex roll-up and the dynamic interaction between shear layer and vortex instability and displaces the vortical structure away from the solid surface for reducing the radiated sound amplitude (Figure 19). [Koop et al. \(2002\)](#) conducted wind tunnel tests including Particle Image Velocimetry (PIV) measurements and observed the sound pressure level in the acoustic far-field was reduced by 3 to 4 dB above

1.25 kHz , which decreased the maximum velocity in the vortex and moved it away from solid surfaces.

Figure 19: Noise generation mechanism and flow control at the flap side-edge

Reference: [Koop et al. \(2002\)](#)

- b) Dielectric Barrier Discharge (DBD): According to [Li, Wang and Zhang \(2013\)](#), plasma technique with discharge actuators has been widely demonstrated to be able to modify the local flow by introducing energy and producing extra momentum for active airflow control. The DBD plasma actuator generally consists of two electrodes which are flush mounted on both sides of the flap side-edge. One of the electrodes is exposed to the ambient air, and the other is insulated by a dielectric material ([Figure 20](#)). A high AC voltage of a particular waveform applied to the exposed electrode weakly ionizes the atmospheric air adjacent to the exposed electrode ([LI; WANG; ZHANG, 2013](#)).

Figure 20: Schematic of DBD plasma actuator

Reference: modified from [Li, Wang and Zhang \(2013\)](#)

The ionized air in the presence of the electric field gradient produced by the electrodes results in a body force that acts on the external air for inducing airflow up to 10 m/s along the actuator surface. Moreau (2007) demonstrated the potential of the plasma actuators on the attenuation of the flow-induced noise. The concept proposed by the author, combines a plasma actuator with a rounded flap tip for producing a coanda effect with the induced airflow, which blows the vortices away from the flap tip (Figure 21).

Figure 21: Coanda effect with plasma actuators in rounded flap side-edge

Reference: modified from Li, Wang and Zhang (2013)

Although both passive control devices and active control techniques mitigate the flap side-edge noise, an aerodynamic and aeroacoustic comprehensive technological evaluation of the different real-scale devices is still a hard task.

2.4 Aeroacoustic and aerodynamic experimental studies in wind tunnel facilities

Numerous experimental airframe noise studies on the side-edge of deployed trailing-edge wing flaps developed since 1970's have shown a strong influence of these elements on the overall aircraft noise. Wind tunnel experiments commonly aim at finding general noise mechanisms and characteristics of a specific model. Acoustic measurements in such facilities are performed as follows:

- a) Far-field experimental measurements are taken with microphone antennas and according to some phased array techniques, as Beamforming, to provide acoustic source localization in experiments. Beamforming techniques have been widely applied for the mapping of pressure oscillation sources and their propagation, which substantially contributes to wind tunnel aeroacoustic measurements; and
- b) Near-field experimental measurements are taken for the evaluation of correlations of acoustic properties with near-field unsteadiness. Some instrumentation used includes hot-wire and hot-film anemometry and PIV.

Such studies are performed in either wind tunnels of closed test sections with difficult far-field prediction and trustworthy aerodynamic characteristics, or anechoic facilities (open test section) with lower aerodynamic fidelity and improved far-field acoustic measurements.

Several aeroacoustic wind tunnel tests have been conducted at NASA Langley Research Center (RADEZTSKY JR; SINGER; KHORRAMI, 1998), NASA Ames Research Center (SODERMAN et al., 2002; HORNE et al., 2005) and the German-Dutch Wind Tunnels (DNW) (KOPIEV; ZAYTSEV; BELYAEV, 2016) and used different measurements on the surface of the model, as steady and unsteady pressure, oil flow, pressure sensitive paint and hot films for flow visualization, and some off-surface measurements, as pitot-probe, PIV, laser velocimetry and laser light sheet, as in Macaraeg (1998), Macaraeg, Lockard and Streett (1999) and Molin et al. (2007), in their research on airframe noise mechanisms associated with high-lift devices. Macaraeg (1998) and Macaraeg, Lockard and Streett (1999) employed a microphone array to obtain the acoustic source maps of the model and quantitative spectra. They observed a noise source located on the edge of the flap at high frequencies. As the frequency decreased, the noise source moved downstream and inboard.

Brooks and Humphreys (2003) also investigated the sound generation mechanism of a flap side-edge and measurements revealed a dominant vortex in the flap resulting from the merging of two upstream vortices, namely strong vortex, formed from the pressure side up to the flap edge, and weaker vortex, formed at the flap side-edge on the suction side, as illustrated in Figure 22. The section cutting planes show an instantaneous photograph of the vorticity field near the flap side-edge, where blue and red denote negative and positive vorticities, respectively. The vortex path is shown by the dashed line. Mid-to-high frequency vortex-edge interaction noise is detected at locations 1 and 2. The low-to-mid frequency noise production results from vortex-edge/surface interactions and is detected at locations 3 and 4. A schematic representation of the spectra of flap side-edge noise and its two main contributors is provided at the bottom left corner of the figure.

Spaid and Lynch (1996) performed experiments to illustrate the flow physics associated with high-lift geometries at full-scale Reynolds numbers, including data of lift and drag measurements and static pressure distributions. Although the authors concluded measurements must be taken under flight Reynolds number conditions, Valarezo et al. (1991) observed the extrapolation of data from low Reynolds number experiments to full-scale is difficult, since important performance parameters do not scale with Reynolds numbers.

Figure 22: Simplified representation of noise production mechanisms of flap side-edge

Reference: [Rossignol \(2013\)](#)

Some experimental tests have been conducted with scale models of commercial aircraft, as Boeing B737 ([SIJTSMA; STOKER, 2004](#)), Boeing B747 ([KIPERSZTOK; SENGUPTA, 1982](#)), Boeing B777 ([HORNE et al., 2005](#)), Airbus A320 ([DOBRZYNSKI et al., 1998](#); [DOBRZYNSKI; GEHLHAR; BUCHHOLZ, 2001](#)), Airbus A340 ([OERLEMANS; BROERSMA; SIJTSMA, 2007](#)), McDonnell Douglas DC-10 ([GUO et al., 2000](#)), Gulfstream G550 ([CASALINO et al., 2015](#); [KHORRAMI et al., 2014](#)) and Bombardier CRJ-700 ([SODERMAN et al., 2002, 2004](#)). Common wind tunnel tests with scale models have been compared with full scale tests for the verification of noise sources and noise reduction technologies applied ([STOKER et al., 2003](#)).

3 EXPERIMENTAL SET-UP

This chapter outlines the experimental procedures employed for the aeroacoustic and aerodynamic analyses of a flap model and the effect of testing different flap tip geometries on the side-edge of the model. Flap model characteristics, dimensions and instrumentations are reported in [Section 3.1](#). [Section 3.2](#) describes the wind tunnel facility and [Section 3.3](#) provides the experimental test conditions. Finally, the experimental aeroacoustic and aerodynamic techniques are discussed in [Sections 3.4](#) and [3.5](#), respectively.

3.1 Flap model

The flap model designed for investigating the phenomena of airframe noise from side-edge was representative of a detailed flap of a conventional commercial aircraft. A 0.70 m chord (c) flap was used for increasing both Strouhal and Reynolds numbers during the tests and the fidelity of results. The unswept model had also 0.70 m span (b) for matching the flap side-edge and microphone array center. Since the model is not comprised of many components, but fairly-simple shapes, as shown in [Figure 23](#), it facilitates measurements and the understanding of the main flow phenomena and their relation to noise emission.

Figure 23: Flap model geometry

Reference: Author

The main structure of the wood-aluminium model is composed of ribs and a simplified iron body-pod formed by two spars and a circular-base (end-plate) fixed to a turn-table mounted at the wind tunnel test section through an iron link and screws

that adjust the angle of attack of the turn-table, hence, the flap model. The two spars have 0.048 m and 0.025 m diameters, respectively, whereas the diameter of the round end-plate is 0.8 m and its thickness is 0.005 m . The end-plate has also a fillet radius to avoid undesirable separations. A removable flap side-edge, with the tested geometries and of approximately 0.08 m span, was used at the tip of the model to facilitate the reproduction of its details and the noise-reduction devices tested.

3.1.1 Dimensions and instrumentation of the model

The dimensions of the model were chosen towards centralizing the flap model with the microphone array. More relevant dimensions are shown in [Table 2](#).

Table 2: Flap model dimensions

Parameters	Flap main element	Flap side-edge
Chord	0.70 m	0.70 m
Span	$0.62\text{ m} - 0.70\text{ m}$	$0.025\text{ m} - 0.80\text{ m}$

Reference: Author

The model instrumentation includes 106 steady pressure taps distributed chord-wise (57 taps along the flap chord ([Figure 24](#))) and span-wise (49 taps along the flap span at seven different heights ([Figure 25](#))) directions on both upper and lower sides of the flap model. The span-wise-distributed pressure taps were used in the verification of the flow uniformity along the flap span.

Figure 24: Chord-wise steady pressure taps

Reference: Author

Figure 25: Span-wise steady pressure taps on the pressure side

Reference: Author

Experiments were performed with and without trip. The trip forces transition eliminating laminar boundary layer effects (low Reynolds number effects). The thickness of the trip tape is provided by Equation 3.1 (BRASLOW; KNOX, 1958), where η_k is a non-dimensionally parameter for a given roughness particle, K is the critical roughness height at a distance x from the leading-edge, and R_x is the Reynolds number based on the length of x . The roughness Reynolds number based on the trip height and the local flow conditions in the boundary layer at the top of the trip is defined as R_k (Equation 3.2) and its value is 250 for trip (BRASLOW; KNOX, 1958). Reynolds number ratio $R_k/\sqrt{R_x}$ was used for the determination of η_k .

A 12 mm long and 0.1 mm thick trip tape was placed over the total span-wise length on the suction side of the flap at $x/c = 0.02$ and on its pressure side at $x/c = 0.06$ to ensure the development of fully turbulent boundary layers and avoid their premature separation at the trailing-edge. The trip positioning did not vary during the experiments.

$$\eta_k = \frac{K}{2x} \sqrt{R_x} \quad (3.1)$$

$$R_k = \frac{U_k K}{\nu_k} \quad (3.2)$$

3.1.2 Coordinate system

3.1.2.1 Flyover position

The center of the turn-table is 0.85 m near the acoustic array center, which resulted in 21° and 24° directivity angles, respectively. The front and top views are shown in Figure 26.

Figure 26: Flap model coordinate system in flyover position. Front (top) and top (bottom) views

3.1.2.2 Sideline position

The flap tip is 1.00 m near the acoustic array center, which resulted in 20° directivity angles. The front and top views are shown in Figure 27.

Figure 27: Flap model coordinate system in sideline position. Front (top) and top (bottom) views

Reference: Author

3.1.3 Flap tip geometries

Different tip geometries were used and tests were performed for four main different configurations, i.e., baseline, which represents a common flap side-edge, rounded flap side-edge, seal flap side-edge, which shows real details on the flap tip, and the new seal flap side-edge, which is the same of the seal tip with a tab. The latter two configurations were also tested with a 22% perforated flap side-edge. Tip models were built from wood and steel and all geometries were attached to the main structure by four screws. Figures 28 and 29 show, respectively, the 3D CAD (Computer Aided Design) views of the flap model tips and a close view of the perforated sheet used in the seal and new seal flap tip geometries. The tests were performed for different configurations regarding three main aspects, namely tip configuration (baseline, rounded, seal or new seal), transition (natural or forced), and perforation location (leading-edge extension, pressure side extension, tab or total perforation).

Figure 28: Base flap tip geometries

Reference: Author

Figure 29: Close view of perforated sheet

Reference: Author

3.2 Wind tunnel facility

Experiments and analyses were performed at LAE-1 wind tunnel facilities ([Figure 30](#)), at the Laboratory of Aerodynamics (LAE) of the Aeronautical Engineering Department at São Carlos School of Engineering - University of São Paulo (EESC-USP) ([CATALANO, 2004](#)). The closed circuit wind tunnel is an atmospheric low-speed facility with a closed test section of 3.00 m length, 1.30 m height and 1.70 m width. It has an eight-blade fan driven by a 110 HP electric motor with seven straighteners downstream the fan and two 54% porosity screens upstream the contraction cone for turbulence reduction, which results in impressive turbulence levels lower than 0.25%. Its maximum design free flow speed is 50 m/s, however, the maximum current free flow speed is 45 m/s due to components endurance and operational safety, according to [Santana et al. \(2010, 2014\)](#).

Figure 30: LAE-1 wind tunnel facility

(a) LAE-1 wind tunnel plan view

(b) LAE-1 wind tunnel 3D view

Reference: Author

The LAE-1 wind tunnel was designed originally for automotive tests, however, it has become a multi-task facility used mainly for aeronautical tests. A background noise reduction process for aeroacoustic measurements has been recently implemented at the wind tunnel. The process was developed in two phases. The first involved the application of melamine foam on the walls of the wind tunnel (regions A and B) without adverse pressure gradient, due to the boundary layer separation risk. The second phase achieved a deeper noise reduction with the addition of polyurethane foam around the fan blade tip-to-wall gap and insulation of the motor (region C), and installation of an acoustic baffle between the corner vanes sections (region D). Figure 31 shows the regions that received the acoustic treatment.

Figure 31: LAE-1 wind tunnel acoustic treatment regions

Reference: Author

Figure 32: LAE-1 wind tunnel treatment results

Reference: modified from [Santana et al. \(2010, 2014\)](#)

The noise treatment processes reduced up to 5 dB the background noise and the turbulence level decreased from the original 0.25% to 0.21%, with no addition of tones on

the turbulence spectra, as shown in Figure 32.

The initial concept of the flap model vertically and horizontally positioned at the wind tunnel test section is displayed in Figure 33.

Figure 33: Flap model views in the wind tunnel test section

(a) Flyover

(b) Sideline

Reference: Author

3.3 Test conditions

The LAE-1 wind tunnel was operated at velocities that range from 26 m/s to 38 m/s , which correspond to Reynolds numbers based on the chord length of the model from 1.02×10^6 to 1.50×10^6 , respectively. The range of Reynolds numbers is given in Table 3. The test flow conditions are the same as those of the wind tunnel location conditions. The atmospheric conditions measured were temperature $T = 20 \text{ }^\circ\text{C}$ and

pressure $P = 91.45 \text{ kPa}$, which implied density $\rho = 1.067 \text{ kg/m}^3$, kinematic viscosity $\nu = 1.746 \times 10^{-5} \text{ m}^2/\text{s}$, dynamic viscosity $\mu = 1.863 \times 10^{-5} \text{ Pa}\cdot\text{s}$ and sound speed $a = 337 \text{ m/s}$. The flap model was tested for deflection angles ranging from $\alpha = -6^\circ$ or $\alpha = 0^\circ$ to 30° in 1° , 2° , 5° or 6° steps, depending on the test.

Table 3: Flow parameters for different tests

U [m/s]	M [-]	Re _{c=0.7} [-]
26	0.076	1.02×10^6
29	0.085	1.14×10^6
32	0.094	1.26×10^6
35	0.101	1.38×10^6
38	0.109	1.50×10^6

Reference: Author

3.4 Aeroacoustic measurements

Aeroacoustic measurements were performed in the experimental phase in the model in both flyover and sideline positions through phased array beamforming techniques for providing acoustic source localization and an estimation of the far-field noise spectrum.

3.4.1 Aeroacoustic transducers

The measurements were taken with an array of 61 microphones flush-mounted on the test section side-wall of the wind tunnel, facing the pressure surface of the flap model for sound pressure acquisition. The G.R.A.S. 46BD microphone set consists of a microphone cartridge with a pressure transducer (40BD) and a preamplifier (26CB) combination, calibrated as one unit with specifications shown in Table 4. The transducer enables TEDS (Transducer Electrical DataSheet) operation and provides a flat response for source localization at a 4 Hz to 70 kHz ($\pm 2 \text{ dB}$) frequency range. Figures 34 and 35 show the typical frequency response of the microphone and free-field directivity correction patterns for different angles of incidence, respectively.

Table 4: G.R.A.S. 46BD microphone set specifications

Parameter	Value
Frequency range ($\pm 2 \text{ dB}$)	4 Hz to 70 kHz
Dynamic range upper limit with preamplifier	166 dB
Set sensitivity at 250 Hz ($\pm 3 \text{ dB}$)	1.45 mV/Pa
Power supply min. to max.	2 to 20 mA
Microphone venting	Rear
Connector type	Microdot 10/32

Reference: [G.R.A.S Sound & Vibration \(2018\)](#)

Figure 34: Typical frequency response of G.R.A.S. 46BD microphone

Reference: Modified from [G.R.A.S Sound & Vibration \(2018\)](#)

Figure 35: G.R.A.S. 46BD microphone free-field corrections for different angles of incidence

Reference: Modified from [G.R.A.S Sound & Vibration \(2018\)](#)

The number of microphones was adjusted for the current project according to [Equation 3.3](#), proposed by [Santana et al. \(2010\)](#).

$$\Delta dB = 10 \log_{10} N_m \quad (3.3)$$

where N_m is the number of microphones of the array and ΔdB is the noise reduction.

The application of $N_m = 61$ to [Equation 3.3](#) enabled the measurement of a source of 17.85 dB intensity lower than that of the wind tunnel background noise by ordinary post-processing techniques.

The microphone array was designed with a modified and optimized spiral geometry ([Figure 36](#)) for measurements at a large frequency band ([FONSECA et al., 2010](#)).

Figure 36: Microphone array design

Reference: Author

The microphones were distributed in a 0.85 m diameter region with the flap side-edge located in their array center, as shown in [Figure 37](#). Each microphone was calibrated prior to noise measurements.

Figure 37: Microphone array position

(a) Flyover

(b) Sideline

Reference: Author

[Figures 38\(a\)](#) and [38\(b\)](#) show the results of the array dynamic range and beamwidth, respectively. Background noise attenuation according to the acquisition time measured by the microphones is shown in [Figure 38\(c\)](#).

Figure 38: Characteristics of LAE-1 wind tunnel noise

Reference: [Pagani-Júnior \(2014\)](#)

The following characteristics of the model and facility were considered for the determination of microphones location in the wind tunnel test section ([ALLEN et al., 2012](#)).

- a) Directivity: source directivity is a relevant factor for the understanding of noise source mechanisms. The sound is generally mapped on a 20° to 160° streamwise plane, where 0° is upstream the noise source. The measurement of the sound directly upstream and downstream a wind tunnel model is difficult due to the wake of the model and the microphones.
- b) Near-field effects: microphones too close to a noise source always cause errors, once, in this region, the acoustic field does not represent the sound propagating to the far-field, which is the aim of our simulation. The distance between the noise source and the microphone should be at least one acoustic wavelength and two source dimensions for avoiding such near-field effects. It puts the microphone

beyond the fluctuations close to the source in the geometric near-field.

- c) Background noise and microphone placement: the microphone placement depends on the background noise level of the wind tunnel and ratio between the signal and the noise. It must be chosen to maximize the distance from the noise source and avoid near-field effects for achieving a 10 dB signal-to-noise difference. A smaller difference can be tolerated if the interfering noise is separated from the data.
- d) Reverberant field: in a hard-walled wind tunnel, the microphone is placed for guaranteeing a direct free field of the noise source, since reflections in the reverberant field would hamper the measurements. The direct field is the region near the source where the source levels are strong enough to dominate the reverberant sound caused by hard-wall reflections.

3.4.2 Acquisition

The microphone array acquisition was performed by an IEPE (Integrated Electronic Piezo-electric) PXI (PCI eXtensions for Instrumentation) system composed of 4 NI (National Instruments) PXIe-4497 boards that hold simultaneously 64 analog inputs of 24 *bits* resolution and maximum of 204.8 *kS/s* sample rate. The microphone data are acquired for 20 seconds. PXI is a platform for measurement and automation systems, where the phased array signals captured by the microphones are processed prior to being sent to the computer.

The acquisition is controlled by a PXIe-8135 controller. RS-232 communications and regular Analog input and output are assessed via PXIe-8430 and PXIe-6341, respectively. A Matlab[®] code developed at LAE was also employed for the data acquisition. It used a data acquisition toolbox and stored the data in a Hierarchical Data Format (HDF5) file, which enables the storage of different file formats. The data were acquired simultaneously with the acquisition parameters described in [Table 5](#). The file information is displayed in [Figure 39](#).

Table 5: Acquisition parameters

Parameter	Value
Acquisition time	20 <i>s</i>
Sample rate	102400 <i>Hz</i>
Number of samples	2048001
Voltage limits	± 10 <i>V</i>
A/D Precision	24 <i>bits</i>
Acquisition Type	IEPE (Microphone Array)

Reference: Author

Figure 39: HDF5 file format contents and structure for data acquisition and post-processing

Reference: Author

3.5 Aerodynamic measurements

Aerodynamic measurements involve steady experiments in the flap model in the flyover position and the aerodynamic wind tunnel tests include force, pressure distribution and flow-field mapping measurements and flow visualization techniques.

3.5.1 Measurements of aerodynamic forces

Balance measurements of the aerodynamic forces acting on the model are performed by an external three-axis balance that measures lift, drag, and pitch moment. The aerodynamic balance used in the experimental tests was built in the Laboratory of Aerodynamics of the Aeronautical Engineering Department from São Carlos School of Engineering - University of São Paulo (EESC-USP). It is positioned beneath the test section of the wind tunnel for automatically modifying the angle of attack of the flap model.

The operation of the strain gage aerodynamic balance is based on the conversion of displacement of two sheets into millivolt (mV) electrical signals. All signals are collected in a Wheatstone bridge circuit and amplified by the HBM (Hottinger Baldwin Messtechnik) module, which enables gains and filtering regulations. They are then recorded on the computer by a data NI AT-M10-16X acquisition sheet of 500 Hz sample frequency. The experiments were performed with a Matlab[®] code that automatically moves the angle of attack of the model and takes the measurement.

3.5.2 Static pressure measurements

Static pressure taps, along with different model positions, were made for enabling observations of the tip effects and the location of the tip vortices along the chord detected as a local pressure difference between the flap suction and pressure sides. The flap main element provides access to the pressure tubes guided out of the wind tunnel test section, where they are further connected to a Scanivalve[®]. Measurements were performed in the wind tunnel test section by a Scanivalve[®] ZOC33/64PxX2 (Zero, Operate and Calibrate) of 0.15% accuracy, which works in a ± 0.72 psi range. It is an extremely compact electronic pressure scanning module specifically designed for use in wind tunnels. Data are acquired by the Scanivalve[®] connected to a local computer via FTP protocol. The procedure involves calibration of zeros and measurement of each channel of the multiplexed system ([SCANIVALVE, 2003](#)).

ZOC33/64PxX2 accepts up to 128 pneumatic inputs duplexed between 64 sensors and converts them into high-level electronic signals. It contains sixty four (64) pressure sensors in eight sensor packs and each sensor pack containing eight sensors, a calibration valve, a duplexing valve, an excitation board, a high-speed multiplexer, and 16 input tubes (banks A and B, 8 inputs each). The module also incorporates a calibration valve that enables the ZOC sensors to be automatically calibrated on-line and purges the input lines of contaminants or condensation. The four modes of operation are operate, calibrate, purge and isolate. The sensors are arranged into eight groups of eight and each sensor has two pneumatic inputs, namely bank A and bank B, which are switched pneumatically by the duplexing valve. Despite the 128 pressure inputs, only one bank of 64 pressure inputs can

be measured at a time. Each group of eight sensors may be a different range. The input voltage was 15 V DC and the output of the module was $\pm 2.5\text{ V DC}$, corresponding to the channel selected by a 6-bit binary address.

3.5.3 Flow-field characterization

Flow-field measurements were performed by an AeroProbe[®] L-shape 7-hole pitot. The curved neck design of the L-Shaped probe enables less downstream airflow blockage, since the shaft is perpendicular to the tip of the probe and removes the shaft from the air stream. The probe is ideal for wind tunnel testing environments because its tip is placed directly in the airflow, whereas the probe is fixed on the side, so that it does not disrupt the air flow (AEROPROBE, 2018). Such transducers were mounted in an automatic traverse system that maps the flow behind the model, close to the flap side-edge and downstream of the trailing-edge, for obtaining the wake characteristics.

A Dantec[®] three-axis traverse system was used for the probe positioning and characterization of the flow. The system can move the probe in three directions at micrometer accuracy. Each axis movement has 0.0125 mm accuracy and was operated by serial communication. It can handle pitot probe for measurements at far-field and near-field. The traverse system moves $X/c = 1.20$ away from the trailing-edge of the model from $Y/b = 0.58$ to $Y/b = 1.42$ in the vertical position and from $Z/c = -0.35$ to $Z/c = 0.28$ in the horizontal position, as shown in Figure 40, with $\Delta Y/b = \Delta Z/c = 0.018$ spacing for the pitot in both directions, which results in approximately 2000 measurement points. Data average was taken from 5 s measurements.

Figure 40: Grid dimensions for flow-field mapping. Lateral (left) and back (right) views

The test measured different flow parameters, such as velocity directions, turbulence levels and flow inconsistencies and data were acquired by either digital pressure transducer modules, or analogical manometers. The high-accuracy probe calibrations define the relationship between the probe pressures measured and the actual velocity vector sensed by the probe and the pressure transducers. A pneumatic tubing was connected from the ports of the multi-hole probe to the pressure measurement system for a correct data acquisition. The stainless steel 3.2 *mm* diameter multi-hole pitot probe is composed of a conventional cylindrical body with seven holes at its tip and enables highly accurate measurements of the magnitude and direction of the flow vectors alongside static and total pressure. The acceptance angle is up to $\pm 30^\circ$ with an error lower than $\pm 1^\circ$. The velocity error is lower than $\pm 1\%$ or ± 1 *m/s* and can have up to 500 discrete aerodynamic calibration points per speed ([AEROPROBE, 2018](#)).

3.5.4 Flow visualization

Separation points, reattachment points, recirculation zones and flow direction were visualized over the flap model surface according to the oil-flow technique. Oil-flow was applied to the flap tripped configuration with different side-edge tips and the entire flap model was painted black for its better visualization.

4 ANALYSES AND PROCEDURES

During the experimental process, aeroacoustic and aerodynamic data were gathered and processed for the obtaining of valid results. [Section 4.1](#) provides the nomenclature used for the data identification, [Section 4.2](#) includes the procedures for the experimental data post-processing, and the instrumentation calibration is described in [Section 4.3](#).

4.1 Nomenclature

The different flap configurations (flap tip geometry, transition type, perforation location and flap position) must be identified for data storage in the experimental phase. Therefore, configuration IDs were created for a better understanding and organization of the tests during the measurement acquisition. Five characters (#1, #2, #3, #4 and #5) were used, of which the first represents the flap model tested ([Table 6](#)), the second is related to the transition type ([Table 7](#)), the third and fourth denote the tip perforation configuration used ([Table 8](#)) and the latter represents the position of the flap ([Table 9](#)).

Table 6: ID first character

Flap side-edge configuration	Character ID 1
Without model	0
Baseline flap side-edge	1
Seal flap side-edge	2
New seal flap side-edge	3

Reference: Author

Table 7: ID second character

Trip configuration	Character ID 2
Without trip	0
With trip	1

Reference: Author

Table 8: ID third and fourth characters

Tip perforation configuration	Character ID 3 & 4
Without perforation	0
Total perforation	1
Perforated leading-edge extension	2
Perforated pressure side extension	3
Perforated Tab	4

Reference: Author

Table 9: ID fifth character

Flap position	Character ID 5
Without model	-
Flyover	F
Sideline	S

Reference: Author

Table 10: Overview of the experiments in the LAE-1 wind tunnel. March 12th to April 12th - July 16th to July 17th - August 22th to August 28th 2018

Tag	ID	Configuration	Description	α [°]	U [m/s]
1E	0000 (-)	None	Empty tunnel	-	10 : 5 : 20
1B	1000 (F)	B	Baseline	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
2B	1100 (F & S)	B + T	Baseline + trip	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
1S	2000 (F)	S	Seal	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
2S	2100 (F & S)	S + T	Seal + trip	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
3S	2110 (F & S)	S + T + P	Seal + trip + total perforation	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
4S	2120 (F & S)	S + T + P (LE)	Seal + trip + perforated LE	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
5S	2130 (F & S)	S + T + P (PS)	Seal + trip + perforated PS	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
1N	3100 (F & S)	N + T	New seal + trip	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
2N	3110 (F & S)	N + T + P	New seal + trip + total perforation	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
3N	3120 (F & S)	N + T + P (LE)	New seal + trip perforated LE +	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
4N	3130 (F & S)	N + T + P (PS)	New seal + trip + perforated PS	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
5N	3140 (F & S)	N + T + P (tab)	New seal + trip perforated tab	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
6N	3123 (F)	N + T P (LE & PS)	New seal + trip + perforated LE and PS	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
7N	3124 (F)	N + T + P (LE & tab)	New seal + trip + perforated LE and tab	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
8N	3134 (F)	N + T + P (PS & tab)	New seal + trip + perforated PS and tab	0 : 5 : 20 20 : 2 : 30	26 : 3 : 38
1R	4100 (F & S)	R + T	Rounded + trip	0 : 5 : 20	26 : 3 : 38

Reference: Author

Note: B = baseline, T = trip, S = seal, P = perforated, N = new seal, R = rounded, LE = leading-edge extension, PS = pressure side extension, F = flyover and S = sideline

Tables 10 and 11 show the different configurations tested and a summary of the experiments conducted, respectively.

Table 11: Flap model experiments in the LAE-1 wind tunnel

Tag	Aeroacoustic measurements		Aerodynamic measurements			
	Flyover	Sideline	Flyover			
	Microphone array		Force	Static pressure	Flow-field	Oil flow
1E	o	o	-	-	-	-
1B	o	-	-	o	-	-
2B	o	o	o	o	o	o
1S	o	-	-	o	-	-
2S	o	o	o	o	o	o
3S	o	o	o	o	o	o
4S	o	o	o	o	-	-
5S	o	o	o	o	-	-
1N	o	o	o	o	o	o
2N	o	o	o	o	o	o
3N	o	o	o	o	-	-
4N	o	o	o	o	-	-
5N	o	o	o	o	-	-
6N	o	-	o	o	-	-
7N	o	-	o	o	-	-
8N	o	-	o	o	-	-
1R	o	o	o	o	-	-

Reference: Author

Note: o = planed and performed experiment, x = planned and not performed experiment and - = unplanned experiment

4.2 Data post-processing

4.2.1 Aeroacoustic measurements

Acoustic measurements were taken in a closed facility and a phased microphone array acquired the data. Two post-processing analyses were used for aeroacoustic measurements. The first provided results of noise spectra in the frequency domain and the second was based on phased array microphones and beamforming techniques for mapping the location of the noise sources and their intensity. Beamforming calculations were performed by conventional beamforming and CLEAN-SC deconvolution methodologies for all data and DAMAS deconvolution methodology for selected cases.

4.2.1.1 Beamforming analyses

The frequency domain Beamforming is computed by the frequency analysis based on the method of Welch, which uses and applies the fast Fourier transform algorithm to estimate the Power Spectra Density (PSD) using a Hanning window and 50% block overlap.

The method transforms the microphone time-history into a Fourier domain, sections the time of series data into segments and calculates their modified periodograms for each segment through the finite Fourier transformations. Finally, it computes the average of the modified periodograms to obtain PSD ([WELCH, 1967](#)). The algorithm is repeated for the creation of the Cross Spectral Matrix (CSM), which correlates each microphone measurement. The main advantages of the Welch's method are reductions in both required core storage and number of computations and yield of fast and high-quality results due to its computational efficiency and simplicity.

A noise source was located according to microphone phased array measurements for the recognition of distinct areas of noise production. A technique known as beamforming processed the acoustic data. The two primary objectives of the measurements were identification of noise production regions and quantification of their strength according to the simultaneous time series acquisition of the pressure measured by the microphones. Beamforming is a source mapping technique based on the optimization of an objective function. Sound pressure signals are transformed into a frequency domain by a vectors base that represents a wave propagation model. The result is a stigmatization of positions and amplitude of aeroacoustic sources. The process begins by measuring a full array cross-spectral matrix for each frequency of interest and defining a grid of potential source locations in the test section of the wind tunnel. A complex array steering vector is computed for each grid point with non-uniform flow and takes into account microphone imperfections and installation effects. Beamforming combines cross-spectral matrices and steering vectors to produce maps of the aeroacoustic source distribution of the model in the wind tunnel ([ALLEN et al., 2012](#)).

Different beamforming techniques, as Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS) and CLEAN based on spatial source coherence (CLEAN-SC) quantifies the position and strength of the noise sources.

The CLEAN-SC, developed by [Sijtsma \(2007\)](#), is an improved version of the traditional CLEAN method of [Högbom \(1974\)](#). It efficiently eliminates secondary lobules consistent with the main lobule of dominant sources on a beamforming map and identifies aerodynamic noise sources whose levels are below those of the secondary lobes of dominant sources. The method requires the post-processing of the results provided by conventional beamforming and is based on an elementary technique called delay and sum, which has shown a promising methodology in aeroacoustics ([OERLEMANS, 2009](#)).

DAMAS method, designed by [Brooks and Humphreys \(2006\)](#), assumes an estimation of a sound pressure at one focal point with a position vector results from the convolution between the discrete acoustic field and the discrete response of the antenna for a point source in the same position. The method was chosen for the analyses of aeroacoustic data, since it shows a more accurate noise source distribution than that obtained by traditional

beamforming techniques.

In aeroacoustic tests in the wind tunnel, the model is exposed to the free stream velocity and responds by producing a complex array of sounds. Several distinct areas of noise production, of which some exhibit interesting internal structures, are usually visualized. The sources create a combination of broadband and tonal noise and no apparent correlation among sounds produced in different areas is observed. In closed wind tunnels, the wall boundary layer adjacent to the microphones creates a signal typically 10 - 20 *dB* higher than the noise radiated from the model. Such an interference is removed through the processing of only the sound correlated between pairs of microphones of the array (ALLEN et al., 2012).

Several beamforming algorithms are described with practical details by Pagani-Júnior (2014), who developed the beamforming code used at the Laboratory of Aerodynamics of the Aeronautical Engineering Department from São Carlos School of Engineering - University of São Paulo (EESC-USP). The process was applied to different optimized grids according to the computed frequency for each model position, as shown in Table 12. It sets the mesh spacing in function of the array beamwidth, considering a coarser mesh for low frequencies and finer mesh for higher frequencies.

Table 12: Grid parameters for beamforming calculations

Parameters	Flyover	Sideline
Width	1.20 <i>m</i>	1.20 <i>m</i>
Height	1.00 <i>m</i>	0.90 <i>m</i>
Depth	0.85 <i>m</i>	0.90 <i>m</i>

Reference: Author

Beamforming was not calculated for all frequencies in the narrowband spectrum towards reducing computational costs. Instead, the frequency band changed from a small Δf (25 *Hz*) for low frequencies to a larger Δf (400 *Hz*) for high frequencies. Table 13 displays the frequency band used for the beamforming calculation analyses.

Table 13: Frequency bands for beamforming calculations

Initial frequency [Hz]	Final frequency [Hz]	Frequency band (Δf) [Hz]
500	1600	25
1650	3200	50
3300	6400	100
6600	12800	200
13200	36000	400

Reference: Author

Seven Regions of Interest (ROI) were created for the beamforming integration regions and assessed the noise contribution measured by each different region of the model. The total noise measured was also studied. The flyover ROIs were created for the total model (ROI 1), total flap side-edge (ROI 2), first flap side-edge region until 30% of the chord (ROI 3), middle flap side-edge region between 30% and 70% of the chord (ROI 4), last flap side-edge region from 70% of the chord (ROI 5), and lower part of the flap span (ROI 6). The last ROI was created for the analysis of the noise produced by the interaction between the wind tunnel wall and the model, which may affect results. The sideline ROI (ROI 7) contains the total model. Figure 41 shows the ROIs used in both measured positions and the number defined for each of them.

Figure 41: Regions of interest for beamforming calculations. Flap model is shown in black and integration regions are shown in colors

Reference: Author

4.2.2 Aerodynamic measurements

Atmospheric conditions were measured at the beginning of each test for the establishment of non-dimensional parameters and comparisons. The atmospheric pressure was measured by a 1 *mmHg* precision calibrated mercury barometer. The temperature was measured inside the wind tunnel by a 0.1° precision thermocouple and the relative humidity was taken in percentage by a 1% precision hygrometer and corrected the calculation of air density.

Equations 4.1 to 4.4 describe the procedure for the calculation of the humid air density according to the ideal gas law for both dry air and water vapor given by Equation 4.1 (ROBERT; ALAN; PHILIP, 1998).

$$\rho_h = \frac{P_d}{R_d (T + 273)} + \frac{P_v}{R_v (T + 273)} = \frac{P_d M_d + P_v M_v}{R (T + 273)} \quad (4.1)$$

Equation 4.2 calculates the partial pressure of the water vapor,

$$P_v = \phi P_{sat} \quad (4.2)$$

and Equation 4.3 calculates the saturation pressure.

$$P_{sat} = 610.78 \cdot 10^{\frac{7.5T}{(T+273)}} \quad (4.3)$$

Finally, Equation 4.4 provides the partial pressure of the dry air,

$$P_d = P - P_v \quad (4.4)$$

The Mach number is computed from Equation 4.5,

$$M = \frac{U}{\sqrt{\gamma R_d (T + 273)}} \quad (4.5)$$

The air viscosity was calculated by Equation 4.6 according to Sutherland viscosity law.

$$\mu = \frac{C_1 (T + 273)^{3/2}}{C_2 + (T + 273)} \quad (4.6)$$

The free-stream velocity is computed from the dynamic pressure by Equation 4.7. Such pressure is measured by a pitot-static probe located at the working section wall. The probe measures both total and static pressures and is connected to a manometer (DP-CALC 8702), whose digital output is the difference between the pressures, which is the dynamic pressure. The instrument shows 0.1 Pa precision and is connected to a computer for automatically acquiring the data prior to each test.

$$U = \sqrt{\frac{2q}{\rho_h}} \quad (4.7)$$

Aerodynamic forces coefficients (lift, drag and pitch moment) were obtained by Equations 4.8, 4.9 and 4.10 and plotted against the angle of attack (α) of the flap model. The wind tunnel speed ranged for the understanding of the Mach number (M) effect on the tests.

$$C_L = \frac{L}{qbc} \quad (4.8)$$

$$C_D = \frac{D}{qbc} \quad (4.9)$$

$$C_M = \frac{M_{0.25c}}{qbc^2} \quad (4.10)$$

The effective aspect ratio was calculated from the results of the inclination of the induced drag curves at the linear range according to the induced drag equation (4.11).

$$C_D = \frac{C_L^2}{\pi eAR} \quad (4.11)$$

Static pressure data were obtained and used in the calculation of the pressure coefficient (Equation 4.12), a non-dimensional parameter that considers the flow over the flap model and immersed in a free-stream with pressure and velocity. P_s and P are the pressure on the flap model and reference pressure, respectively. The latter was taken at the wind tunnel test section and post-processed for the production of C_p data.

$$C_p = \frac{P_s - P}{q} \quad (4.12)$$

Wake and flow mapping measurements were performed by a 7-hole probe and the data were stored in a Tecplot[®] data format for an efficient plotting and comparisons between flap side-edge geometries. The three-velocity components (u, v and w) were obtained by the probe and adimensionlized by Equations 4.13, 4.14, and 4.15.

$$u^* = \frac{u}{U} \quad (4.13)$$

$$v^* = \frac{v}{U} \quad (4.14)$$

$$w^* = \frac{w}{U} \quad (4.15)$$

4.3 Instrumentation calibration

4.3.1 Microphone array calibration

The microphone array was calibrated by an NC-74 sound calibrator (CO, 2003) of $94 \text{ dB} \pm 0.3 \text{ dB}$ sound pressure level, $1 \text{ kHz} \pm 2\%$ frequency and 1.0 Pa reference pressure fluctuation for the microphone adapter. NC-74 is a compact and lightweight unit and incorporates a sensor that detects atmospheric pressure and requires no atmospheric pressure compensation. A CPU controlled the signal amplitude according to the information provided by the sensor. The unit always provided the correct output for achieving constant sound pressure level, regardless of fluctuations in the atmospheric pressure. Microphone data were acquired during calibration and a digital band-pass filter created the data used for the calculation of microphones sensitivity, which ranged from 1.45 to 2.60 mV/Pa .

4.3.2 Balance calibration

The aerodynamic balance was carefully calibrated prior to the experiments through the loading of known weights for the achievement of the linear relation between voltage and force. Balance calibration refers to the identification of equations that calculate the loads acting on the model according to the output voltage signals. Figure 42 shows the calibration results. The calibration is expressed by a first-order polynomial equation for each aerodynamic force. The accuracies related to lift, drag, pitch moment and angle of attack are 0.01 N , 0.01 N , 0.01 Nm and 0.1° , respectively.

Figure 42: calibration of aerodynamic forces

Reference: Author

4.3.3 Scanivalve calibration

ScaniValve[®] ZOC33/64PxX2 pressure sensors were arranged in blocks of 8 units. Each block has its own individual calibration valve composed of four modes of operations, namely operate, calibrate, purge and isolate. The modes are selected through the application of control pressures in a predetermined and logical order. ZOC33 calibration valves use

valve logics, and the valve defaults to the purge mode when no control pressures are applied. ZOC33 shows 10 *in* $H_2O = 25.40 \text{ cm}$ and $\pm 0.15\%$ full scale range ($\pm 0.038 \text{ cm}$) accuracy after calibration.

4.3.4 7-hole probe calibration

The L-shaped 7-hole pitot probe used for the flow mappings was calibrated at the LAE. It faced a uniform flow in the test section of the wind tunnel with specified angles from a range of $\pm 30^\circ$ with 5° precision. The probe measured its output to define the relationship between the measured velocity and the actual one. Two calibration functions were created from the results: one that used a classic polynomial fit and another with a trained neural network. Such a network achieves errors lower than 1.5° and is used when flow angles are smaller than the calibration maximums (30°) to avoid extrapolations. Figure 43 shows the neural network calibration for angles α and β and velocity u^* .

Figure 43: 7-hole probe neural network calibration

5 RESULTS AND DISCUSSIONS

This chapter outlines results of a series of aerodynamic and aeroacoustic experiments performed with different side-edge treatments applied to the flap model in the LAE-1 wind tunnel. The tests investigated the flow-field and helped understanding the physics responsible for the noise generation mechanism at the flap side-edge. Comparisons of the treatments with the baseline configuration and effect of different parameters were conducted. [Sections 5.1](#) and [5.2](#) discuss the aerodynamic and aeroacoustic measurement results, respectively.

5.1 Results of aerodynamic measurements

5.1.1 Flap aerodynamic loading

The evaluation of the flap aerodynamic loading aimed at knowledge on the additional lift compensation produced by the flap with no main wing element. The difference in the angle of attack was obtained through comparisons of computational results by XFLR5[®] tool for the flap model without the principal element (baseline flap model) and PowerFlow[®] software for the flap model with the principal element (flap side-edge). XFLR5[®] software designs and analyzes airfoils, wings and planes operating at low Reynolds numbers. The analysis was based on the Vortex Lattice Method and 3D Panel Method. Program XFOIL[®] is used in XFLR5[®] for the design and analysis of subsonic isolated airfoils for a range of angles of attack. PowerFlow[®] is CFD software based on Lattice Boltzmann equations.

Viscous simulations were performed in XFLR5[®] and PowerFlow[®] as a rough measure for the obtaining of the change in the angle of attack. Both simulation conditions were the same of those of wind tunnel and the results are shown in [Figure 44](#).

The lift coefficient produced at $\alpha = 0^\circ$ by the flap side-edge was 1.34. It decreased up to 0.37 in the baseline flap model with no main wing element for the same deflection. The angle of attack increase changes the lift coefficient, therefore, an angle of attack $\alpha = 26^\circ$ was required for the flap model to compensate for the lift coefficient decrease caused by the use of the flap with no main wing element.

[Figure 45](#) shows the results of the convergence variation history of lift and drag coefficients obtained by PowerFlow[®] for the flap model at $\alpha = 0^\circ$. The lift and drag coefficients are 0.388 and 0.042, respectively. PowerFlow[®] simulations were conducted in the Laboratory of Aerodynamics of the Aeronautical Engineering Department from São Carlos School of Engineering - University of São Paulo (EESC-USP).

Figure 44: Computational lift coefficients for the flap side-edge and baseline flap

Reference: Author

Figure 45: Convergence results of lift and drag coefficients for the baseline flap at $\alpha = 0^\circ$

Reference: Author

5.1.2 Pressure distribution

Static pressure measurements were simultaneously taken for the entire chord and span direction. Figure 46 shows the expected behavior for a pressure distribution around the flap chord of the baseline and seal flap side-edge in the closer side-edge region. The effect of the transition trip was also evaluated in terms of static pressure in the model. The comparison between the tripped and untripped cases, for several angles of attack and velocities, showed the trip device exerts a small effect on the suction peak and laminar boundary layer transitions in tripped and untripped flap model. The uncertainty of the pressure coefficient for the most critical case was ± 0.0015 , according to the procedure of experimental uncertainty proposed by Robert, Alan and Philip (1998).

Figure 46: Pressure distribution around tripped and untripped flap model at $\alpha = 26^\circ$ and $M = 0.109$

Reference: Author

As shown in Figure 47, both baseline and rounded pressure distributions include one suction peak on the upper surface, indicative of a flap tip vortex. The side-edge vortex in the flap side-edge influences the pressure distribution in both pressure and suction side from the flap tip ($y/b = 1$) until $y/b = 0.77$. The seal and new seal flap side-edge configurations show the typical leading-edge suction on the upper surface while a moderate lower-surface pressure gradient is generated by moving away the side-edge vortex system. The location of the backward suction peak in the rounded tip suggests the core of the upstream vortex moves aft as it connects downstream.

The Suction peak is also affected by the vortex along the span of the model (Figure 48). Seal and new seal tips on the flap side-edge increase the span-wise uniformity.

Figure 47: Chord-wise pressure distribution comparison at $\alpha = 26^\circ$ and $M = 0.109$

Reference: Author

Figure 48: Comparison of span-wise pressure distributions. Span-wise taps are located on the suction side from $x/c = 0.02$ to $x/c = 0.65$ and for $y/b = 0.95, 0.88, 0.77, 0.65, 0.51, 0.35$ and 0.18 at $\alpha = 26^\circ$ and $M = 0.109$

(a) 2D chord-wise and span-wise taps location

(b) 3D chord-wise and span-wise taps location

(c) Comparison of span-wise pressure distributions

Reference: Author

Figure 49 displays the pressure distributions over the seal flap side-edge in the chord-wise direction at different flap deflection angles. The distributions show an overall raise in the suction peak and section lift coefficient due to the increase in the angle of attack up to $\alpha = 28^\circ$. The suction peak decreased from $\alpha = 28^\circ$ to $\alpha = 30^\circ$, which is associated with the leading-edge format and the low aspect ratio. The suction peak also moved from the lower surface at $\alpha = 0^\circ$ to the upper surface at $\alpha = 5^\circ$; from $\alpha = 5^\circ$, it begins to move to the leading-edge. The suction side of the element was affected by a separation that starts at $x/c \approx 0.3$ for high angles of attack. For $\alpha = 30^\circ$, the separation growth starts at $x/c \approx 0.1$.

The application of a perforated flap side-edge strongly affects the pressure distribution of the flap. As shown in Figure 50, the suction peak decreased for the two perforated side-edge configurations and, consequently, the lift coefficient was affected, which indi-

Figure 49: Pressure distribution over the seal flap side-edge at $y/b = 1$, $M = 0.109$ and different angles of attack

Reference: Author

cates an influence of a perforated tip on the aerodynamic performance. Perforated flap side-edge tips produce 10% lower section lift coefficient on the flap in comparison with the non-perforated configurations.

Figure 50: Effect of perforated tips on pressure distribution at $\alpha = 26^\circ$ and $M = 0.109$

Reference: Author

Figure 51 shows a deeper perforation analysis for seal and new seal side-edge configurations. In both cases, the pressure distribution behavior does not show large differences with perforation in a specific part of the side-edge tip (leading-edge extension, pressure side extension or tab), whereas a total perforation strongly affects the aerodynamics of the flap side-edge, as previously shown in Figure 50.

Figure 51: Effect of perforation location on the pressure distribution at $\alpha = 26^\circ$ and $M = 0.109$

Reference: Author

5.1.3 Aerodynamic forces

The aerodynamic loading on the flap was caused by the pressure differential between the pressure and suction surfaces. Force measurements were taken with the different flap tips applied to the side-edge of the model for the quantification of the aerodynamic penalty associated with their use. Additionally, force measurement results verified the results addressed in the pressure distribution analysis. The forces were measured at $M = 0.076$ due to balance operational safety. The angles of attack measured ranged from $\alpha = -6^\circ$ to 30° in 1° steps. The uncertainties related to lift, drag and pitch moment coefficients are ± 0.0020 , ± 0.0038 , ± 0.0025 , respectively, according to the analysis of experimental uncertainty proposed by Robert, Alan and Philip (1998).

Results of balance measurements of the baseline flap side-edge were compared with computational ones obtained by XFRL5[®]. Figure 52 displays the comparisons of lift and drag coefficients. The lift coefficient curves illustrated in Figure 52(a) are consistent with

small differences in the probable angle of attack for zero lift and maximum lift coefficient. Figure 52(b) shows results of drag coefficient. Despite the concordance between $\alpha = -4^\circ$ to 12° for lower and higher angles of attack, the computational results were lower than the experimental ones due to the difficult calculation of the separation and transition points by XFRL5[®], which altered the experimental curve trend.

Figure 52: Experimental and computational results for the baseline flap side-edge at $M = 0.076$

Reference: Author

Figure 53 displays the aerodynamic performance of the non-perforated tips including measurements of the lift, drag and pitching moment coefficients. The use of flap tip treatments shows (Figure 53(a)) the addition of the seal and new seal tips has a clear effect on the slope of the linear part of the curve. Both tips increased the maximum lift coefficient ($C_{L \max}$) by margins greater than the calculated uncertainty due to the reduction in vortex formation on the tip of the model with a probably increase, without significant changes, in the angle of maximum lift coefficient. This behavior suggests the tip treatments alter the overall flap efficiency. The two different slopes of the curves were caused by the separation on the flap suction surface that started at approximately $\alpha = 8^\circ$.

The angle of attack for zero lift was always the same, i.e., $\alpha = -7^\circ$, which suggests an increase in the effective aspect ratio when the the tip vortex moves away from the flap tip in the span-wise direction. The vortex movement exerts a key effect on the noise generated by the flap tip vortex interaction with the flap side-edge. Table 14 shows the effective aspect ratio calculated from the results of the inclination of the curves in Figure 53(e) at the linear range. The effective aspect ratio increase is a function of the tips added to the flap side-edge. The maximum lift coefficient measured at $\alpha = 30^\circ$ increased with the seal and new seal tips. The maximum lift coefficients are 1.32 for the baseline and rounded cases and 1.63 and 1.65 for the seal and new seal cases, respectively, which means an approximately 25% increment.

Table 14: Effective aspect ratio calculated for different flap side-edge tips

Flap side-edge tip	Aspect ratio
Baseline	2.00
Rounded	2.06
Seal	2.46
New seal	2.56

Reference: Author

Figure 53(d) shows the effects of the different tips on the drag polar. The drag polar improved with the use of the seal and new seal configurations mainly due to the lift increase in the linear range. The drag coefficient was larger for all angles of attack, due to a slight increase in the pressure drag, confirmed by the increase in the drag coefficient for zero lift in comparison with the baseline case (Figure 53(b)). The increase in the drag coefficient with those tips was related to the material added in both cases in comparison with the baseline and rounded tips. Figure 53(b) also illustrates the increase in the minimum drag coefficient ($C_D \min$) with the increment in the effective aspect ratio of each tip. The two more negative cases in Figure 53(c) mean the flap aerodynamic loading was higher due to the vortex shifted. According to Figure 53(f), baseline and rounded flap tips were aerodynamically less efficient than the other tips, represented by the higher values in the curves of the seal and new seal cases. The results for the rounded tip are very similar to those of the baseline case, with differences smaller than the uncertainty calculated for lift, drag and pitch moment components, as addressed by Storms and Ross (1996).

The perforated material at the flap side-edge enables a transpiration velocity through the material, which changes the pressure differential. Figure 54 shows the aerodynamic analyses of the perforated tips. The lift coefficient was greater in non-perforated cases for all angles of attack. Such a perforated treatment exerts less lift at the side-edge due to its permeability. The permeability of the perforated material was related to the number of perforations per linear inch and the relative density of the material to the solid base material. Figure 54(d) shows an improvement in the drag polar curves with the perforated tips, probably due to the pressure drop imposed on the flow passing the perforated material and producing an axial force. The drag coefficient was almost equal with and without perforations, nevertheless, the slight increase in the aerodynamic drag for angles of attack ranging from $\alpha = -6^\circ$ to 22° was due to the nature of the perforated material. Although the increment in the lift coefficient (Figure 54(a)) exerted a stronger effect than the increment of the drag coefficient (Figure 54(b)) for perforated tips, the small increment in the drag by porous devices was confirmed in other investigations (ANGLAND, 2008; ANGLAND; ZHANG; MOLIN, 2009; MOLIN et al., 2007; MORALEDA; CATALANO), 2014, 2013). The flow through the perforated material resulted in a pressure loss across the material, hence, a drag force.

The decrease in the aerodynamic efficiency (Figure 54(f)) is adverse for the main wing element case, but is less important for the flap case, since it is used only in landing and taking-off phases. During the landing phase, when the flap is at its maximum deflection, the drag increment decelerates the aircraft until the flap side-edge vortex has been reduced; therefore, a noise reduction is probably achieved. According to the measurements of the aerodynamic forces and calculations of aerodynamic efficiency, the aerodynamic impact of the perforated new seal flap side-edge was the least efficient.

The comparison of the results of the induced drag (Figure 54(e)) are shown in Table 15. The effective aspect ratio was smaller with the two perforated configurations, since the non-perforated material prevented any transpiration velocity through the flap side-edge. Figure 54(c) shows the moment coefficient of the perforated tips also were more negative for higher angles of attack than the other cases, which increased the flap aerodynamic loading and suggests an effective vortex shifted. The aerodynamic centers of the flap were fixed at 26% chord for the baseline and rounded tips, and 24% chord for the seal and new seal tips.

Table 15: Effective aspect ratio calculated for perforated flap side-edge tips

Flap side-edge tip	Aspect ratio
Baseline	2.00
Seal	2.46
Seal (perforated)	2.28
New seal	2.56
New seal (perforated)	2.37

Reference: Author

The results in Figure 55 show the effect of the perforation location on the flap with the seal side-edge tip in its aerodynamic performance. As expected, the aerodynamic behavior of the seal with perforated leading-edge extension tip was similar to that of the seal tip. Figures 56 and 57 show the effect of the perforation location on the flap with the new seal side-edge tip in aerodynamic performance with one and two perforated elements, respectively. As addressed in the previous analysis, the aerodynamic performance of the new seal with perforated leading-edge extension or tab and the new seal with perforated leading-edge extension and tab was almost identical to that of the new seal tip. In both analyses, the similitude between curves of perforated and non-perforated flap side-edge tips were related to the fact that most of the material continues solid and, therefore permeabilities, between the configurations are similar.

Figure 53: Effect of tips on aerodynamic performance at $M = 0.076$ and $Re = 1.02 \times 10^6$

Reference: Author

Figure 54: Effect of perforated tips on aerodynamic performance at $M = 0.076$ and $Re = 1.02 \times 10^6$

(a) Lift coefficient

(b) Drag coefficient

(c) Moment coefficient

(d) Polar

(e) Induced drag

(f) Aerodynamic efficiency

Reference: Author

Figure 55: Effect of the perforation location on the seal flap side-edge in aerodynamic performance at $M = 0.076$ and $Re = 1.02 \times 10^6$

Reference: Author

Figure 56: Effect of the perforation location on the new seal flap side-edge in aerodynamic performance with one perforated element at $M = 0.076$ and $Re = 1.02 \times 10^6$

(a) Lift coefficient

(b) Drag coefficient

(c) Moment coefficient

(d) Polar

(e) Induced drag

(f) Aerodynamic efficiency

Reference: Author

Figure 57: Effect of the perforation location on the new seal flap side-edge in aerodynamic performance with two perforated elements at $M = 0.076$ and $Re = 1.02 \times 10^6$

Reference: Author

5.1.4 Wake mapping

The wake of the flap model was mapped at several horizontal planes by a 7-hole probe. The three non-dimensional velocity components u^* , v^* and w^* were measured at different constant heights from $Y/b = 0.58$ to $Y/b = 1.42$ (flap tip face $y/b = 1.00$). The wake mapping measurement were taken at $\alpha = 5^\circ$ and $M = 0.076$ due to 7-hole pitot and Dantec® three-axis traverse system operational safety.

The plots shown in [Figure 58](#) contain the profiles of the velocity magnitude for different planes. The most immediate effect of the seal tip configurations was the conversion of the “jet-like” vortex of the baseline flap tip into a “wake-like” vortex, i.e., a vortex core of higher velocity into a vortex core of lower velocity ([LEE; PEREIRA, 2010](#)). In all side-edge configurations from $Y/b = 0.58$ to $Y/b = 1$ between $Z/c = -0.28$ and $Z/c = -0.14$, the velocity decrease was related to the wake produced by the trailing-edge of the flap. In the baseline flap side-edge at $Y/b = 1$, the effect exerted by the vortex was not present in the other flap tips. For seal tips, the wake profiles show the minimum velocity regions are behind the trailing-edge of the flap at $Z/c = 0.00$ and for such tip configurations, the minimum velocities were displaced to the right in the transition from $Y/b = 1.14$ to $Y/b = 1.28$, which indicates the vortex was shifted due to variations in the tip of the model.

[Figures 59, 60](#) and [61](#) display the wake profiles of velocities u^* , v^* and w^* , respectively. The wake profiles for the axial velocity (u^*) show a small decrease in velocity u^* for lower heights (from $Z/c = -0.35$ to $Z/c = -0.14$) caused by the trailing-edge of the model. For upper heights (from $Z/c = 0.00$ to $Z/c = 0.28$), the velocity reduction is related to the vortex behind the flap model. The wake profiles for velocity v^* indicate the flow downstream the flap model is moving in the clockwise direction and in the counterclockwise direction for velocity w^* . The values decrease for the three velocity components with the use of the seal and new seal flap side-edge tips. Such a decrease effect is more pronounced for perforated side-edge configurations.

[Figure 62](#) displays the wake profile of velocities v^* and w^* across the vortex core of each configuration. The maximum values were not the same for the negative and positive sides and the asymmetry in the profile is visible for velocities v^* and w^* . [Figure 62\(a\)](#) shows a slower decrease on the right side and [Figure 62\(b\)](#) shows it on the left side, which corresponds to the areas of lower axial velocity for each velocity component. The perforated tips also displaced the vortex away (up and right to the pressure side) from the flap tip surface and reduced its intensity. The vortex core height for velocity v^* in Y axis was located at $Y/b = 1.04, 1.11, 1.21, 1.14, 1.18$ and 1.11 in the baseline, rounded, seal, seal (perforated), new seal and new seal (perforated) side-edge tips, respectively, and for velocity w^* in Z axis, it was located at $Z/c = 0.07, 0.04, 0.04, 0.04, 0.00$ and 0.00 in the baseline, rounded, seal, seal (perforated), new seal, new seal (perforated) side-edge tips, respectively.

Figure 58: Profiles of velocity magnitude in the Y axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Figure 59: Profiles of velocity u^* in the Y axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 60: Profiles of velocity v^* in the Y axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 61: Profiles of velocity w^* in the Z axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 62: Profiles of maximum velocity v^* in the Y axis and maximum velocity w^* in the Z axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

Reference: Author

5.1.5 Flow mapping

A 7-hole probe investigated the flow-field downstream the flap model. The axial velocity, tangential velocity and vorticity were the most relevant flow measurements in the study of the flow-field. The flow mapping measurement were taken in a vertical plane at $\alpha = 5^\circ$ and $M = 0.076$ due to 7-hole pitot and Dantec[®] three-axis traverse system operational safety. The flow-field maps of velocities u^* , v^* , w^* and the vorticity are shown in Figures 63, 64, 65 and 66, respectively.

The velocity maps for velocity u^* show a region of reduced velocity at approximately $Z/c = 0.00$ position, near the flap side-edge generated by the vortex. A small region of reduced flow speed downstream the pressure side of the model is probably caused by a wake formed at the trailing-edge, as shown in Figure 58. The lowest velocity value reaches approximately $u^* = 0.95$. The velocity maps in Figures 63(c) to 63(e) revealed the flow was moving up from the tip surface due to the use of the seal flap side-edge tips.

The tangential velocities (v^* and w^*) are also important components for the understanding of the flow behavior behind the flap model. The vortex is composed of the spinning motion of the transversal velocity in the Y and Z axes. The maps in Figures 64 and 65 show negative and positive regions separated by a perpendicular line at one of the axes. The velocity maps for velocities v^* and w^* indicate the flow downstream of the flap model strongly reduced its intensity varying the flap tip. The regions of increased and reduced velocities seem to be slightly different and the asymmetry perceived was generated by the angle of attack relative to the incoming flow.

Figure 63: Velocity u^* in the X axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

Figure 64: Velocity v^* in the X axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

Figure 65: Velocity w^* in the X axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

Figure 66: Vorticity in the X axis at $\alpha = 5^\circ$, $M = 0.076$ and $X/c = 1.20$

Finally, the vorticity maps show a large vortex downstream the flap tip. As illustrated in Figure 62, the vortex seems to be weakened for the perforated tips that significantly reduced its intensity. As addressed in the wake mapping analysis, the vortex system was displaced up and right to the pressure side and the maps of the new seal side-edge tip indicate the tab reduced the vorticity movement to the suction side of the flap model.

5.1.6 Flow visualization

The oil-flow visualization technique, applied at the flap tip surface, investigated the flow behavior around the flap model and particularly, the pathlines and three-dimensional effects near the flap side-edge. Figures 67 and 68 display the results of the oil-flow visualization for the baseline, rounded and perforated flap tips. The flow visualizations were also analyzed and the flow pattern on the side-edge tips were sketched. The visualizations clearly exhibited the pathlines created by the primary tip vortex moving from the pressure to the suction side on the tip face. The most visible line is the vortex secondary attachment line induced by the reattachment of the shear layer separated from the pressure side of the flap. The vortex grew in size in the free-stream direction, as indicated by the primary attachment line moving towards the suction surface of the flap side-edge. The results are in agreement with those of Rossignol (2013), who sketched the streamlines of the flow visualization on a flap tip face. The main differences between baseline and seal flap side-edge tips are the recirculation zone produced by the vortex near the pressure side due to the presence of the seal and a discontinuity on the leading-edge lines resulting from the three-dimensional interaction of the vortex with the turbulence caused by the seal.

Figure 67: Flow-field sketches on the flap tip face at $\alpha = 26^\circ$ and $M = 0.109$

Figure 68: Flow visualization on the flap tip face at $\alpha = 26^\circ$ and $M = 0.109$

(a) Baseline flap side-edge

(b) Seal flap side-edge

(c) Baseline flap side-edge
leading-edge region

(d) Seal flap side-edge
leading-edge region

(e) Baseline flap side-edge
mid-chord region

(f) Seal flap side-edge
mid-chord region

(g) Baseline flap side-edge
trailing-edge region

(h) Seal flap side-edge
trailing-edge region

5.2 Results of aeroacoustic measurements

5.2.1 Background wind tunnel noise

The LAE-1 wind tunnel generates a significant amount of noise. The analysis of the background noise aims at assessing its influence on the measurements, regarding spectra, beamforming maps, and Mach scale factor. Several measurements were performed for the obtaining of the background noise observable in the LAE-1 wind tunnel test section, where the phased array microphones are located. Figure 69 shows the wind tunnel sound pressure levels measured for 0.076, 0.085, 0.094, 0.101 and 0.109 Mach numbers. The first spectral results in Figure 69(a) displayed for Strouhal number provided an insight on the frequency scales with velocity. High-frequency peaks are caused by the Power inverter that rotated the fan of the wind tunnel. No peaks were detected between low to medium frequencies, which provided a broadband noise in all range with higher levels at low and mid frequencies.

Figure 69: LAE-1 background wind tunnel noise

(c) OASPL (Filtered Overall Sound Pressure Level)

Reference: Author

Mechanisms of background noise sources were investigated by the Mach scale factor (N). [Figure 69\(b\)](#) shows the Mach scale factor as an average of the five velocities used and [Figure 69\(c\)](#) displays a comparison between the OASPL obtained for the Mach numbers tested and expected curves. The scale estimated for the OASPL was found through the calculation of an average for the value of N . The results are in concordance with those expected as monopole scales were produced. Frequency and Mach scales are represented by Strouhal numbers calculated with the free-stream velocity.

The sources of wind tunnel background noise are the fan system (variables that contribute to fan noise are hub and tip diameter, rotational speed, number of blades and blade-pitch angle), wall boundary layer, test-dependent hardware, and microphone self noise (boundary layer effect over the microphones, screen or cavity perturbations, electronic noise, and free-stream turbulence) ([ALLEN et al., 2012](#)).

5.2.2 Uncertainty analysis of beamforming methodology

Apart from the conventional beamforming and CLEAN-SC deconvolution analyses for all flap tip geometries, DAMAS deconvolution methodology was employed for the selected cases. The comparison of the three different beamforming methodologies tested aims to explain the behavior behind methodological procedures, rather than to find the most correct beamforming methodology.

[Figure 70](#) displays the results of measurements calculated according to the three different methodologies in the largest Regions of Interest (ROIs 1 and 7). The spectra show the broadband noise follows the same shape for all methodologies. Nevertheless, the noise spectra calculated by conventional beamforming and DAMAS preserved the same behavior and showed similar tendencies at low and mid frequencies. CLEAN-SC and DAMAS revealed a higher slope in the high frequency range for both flyover and sideline measurements.

By their own formulations, the conventional beamforming and DAMAS methodology produce a continuum spectrum without peaks. CLEAN-SC concentrated the spectral energy of the coherent noise sources in a single point, which produced pronounced peaks that changed the levels in the spectrum mainly at low frequencies.

The beamforming drawback is related to the computational time that significantly impacts the time for the analyses of the results, depending on the methodology used. DAMAS requires very high computational time with no additional information provided by conventional beamforming and CLEAN-SC in less time. The following aeroacoustic results were obtained by conventional beamforming. The methodology produces results in similar trends to CLEAN-SC and DAMAS because the flap side-edge noise was considered the prominent and dominant noise source during the aeroacoustic tests with no interference of additional sources.

Figure 70: Effect of the beamforming methodology (conventional, CLEAN-SC and DAMAS) on the seal flap side-edge tip at $\alpha = 26^\circ$

Reference: Author

5.2.3 Analysis of beamforming maps

Beamforming maps of the four main configurations (baseline, rounded, seal and new seal) were also plotted for the assessment of the noise maps obtained at the spectra for the three selected frequencies. Figures 71 and 72 show the resulting beamforming maps in ΔdB for flyover and sideline measurements, respectively, for a 5000 till 14000 Hz range. Although computed from 500 to 36000 Hz , they are not shown in all range, since the large array beamwidth and the coherence loss affect the results for low and high frequencies, respectively. Most maps showed a defined noise source, however, the apparently random shape of some maps with no consistent source means any noise source was present in the model region and only side-lobes from other sources were observed. The inconsistent source is related to a higher decrease in the radiated noise for those specific configurations and frequencies. The array of microphones on flyover maps identified a strong noise source from the flap side-edge located at $x/c \approx 0.18$ for baseline, seal and new seal configurations, which corresponds to the first part of the flap side-edge (leading-edge region) local flow-field noise described by Drobietz and Borchers (2006). On the other hand, the rounded flap side-edge moved the main noise source to the last flap side-edge region at $x/c \approx 0.68$. Although the sideline mapping results are not useful as flyover measurements, they confirmed the noise sources are mainly concentrated in the same locations, as flyover maps, which indicates the most relevant noise source was located in the region of interaction between the vortex and the flap side-edge surface. According to the maps, the model shows no consistent map in the baseline case, but only side-lobes mainly of the background noise. In general, noise source maps clearly revealed the way the acoustic radiated noise decreased from low- to high-frequency spectra.

Figure 71: Beamforming maps of noise source localization for a flyover position obtained at $\alpha = 26^\circ$ and $M = 0.109$. Baseline flap side-edge (a-c), rounded flap side-edge (d-f), seal flap side-edge (g-i) and new seal flap side-edge (j-l). Black refers to the flap model and red denotes the integration region

Reference: Author

Figure 72: Beamforming maps of noise source localization for a sideline position obtained at $\alpha = 26^\circ$ and $M = 0.094$. Baseline flap side-edge (a-c), rounded flap side-edge (d-f), seal flap side-edge (g-i) and new seal flap side-edge (j-l). Black refers to the flap model and red denotes the integration region

Reference: Author

5.2.4 ROIs analysis

According to the results in [Figure 73\(a\)](#), the predominant noise originates from the side-edge region (ROI 2). The strongest noise level of ROI 2 was produced by the leading-edge region (ROI 3), where the vortex of the turbulent boundary layer on the

pressure side moved across the lower flap side-edge. At this point, the vortex interacted with the surface of the flap side and pressure fluctuations were converted into acoustically radiated noise. The low-frequency noise was radiated from the middle side-edge region (ROI 4). The high-frequency noise was also produced by the turbulent end-plate interaction with the wind tunnel in the lower part of the flap span (ROI 6). [Figure 73\(b\)](#) shows a comparison of the spectra of ROIs 1 and 7, both with a slope $m = -30 \text{ dB/dec}$ from a $St = 70$.

The similarity between the spectra curves does not necessarily mean all different ROIs of the model produce noise in a similar spectrum; it may be related to the integration of side lobes of a higher source in a single place.

The following aeroacoustic results were calculated for ROIs 1 and 7 in the flyover and sideline positions, respectively.

Figure 73: Acoustic spectrum variation with ROIs obtained at $\alpha = 26^\circ$

Reference: Author

5.2.5 Trip tape effect

Different investigations have addressed the importance of the use of a trip device for increasing Reynolds number, ensuring the development of fully turbulent boundary layers, preventing premature separation of the boundary layers at the trailing-edge of the model, and reducing the appearance of trailing-edge tones ([ROSSIGNOL, 2013, 2010](#)). Acoustic measurements were performed with and without the sand trip tape for comparisons of the tests ([Figure 74](#)). A deep insight about the spectra variation between the cases with and without trip for different angles of attack shows the effect of tripping of the model is not higher than $\pm 2 \text{ dB}$ in all frequency range ([Figure 74\(a\)](#)). Such a variation exerted no significant and measurable impact on the acoustic emission for a specific angle of attack, as shown in [Figure 74\(b\)](#) for $\alpha = 26^\circ$.

Figure 74: Effect of trip tape on the seal flap side-edge at $\alpha = 26^\circ$ and $M = 0.109$

Reference: Author

5.2.6 Effect of angle of attack

Figures 75 and 76 show results of the acoustic spectrum variation with six and two different flap deflection angles for flyover and sideline measurements, respectively. Small variations were detected for low to mid frequencies for the baseline flap side-edge in flyover position; in high frequencies, an increase in the angle of attack caused a small increase in the broadband noise. The noise pressure level for the other tips was affected by the higher angles of attack for $\alpha = 26^\circ$, 28° and 30° . These tips significantly reduce the vortex at higher angles of attack, which causes the baseline trend to reverse. For such cases, an increase in the angle of attack decreased the spectrum. The acoustic spectrum in the sideline position does not increase in function of higher angles of attack and is reduced in baseline, rounded, seal and new seal tips.

5.2.7 Strouhal and Mach number scale effects

The effects of Strouhal and Mach scale are important for the assessment of noise mechanisms for the flap model. Analyses were performed through tests with five and four different Mach numbers for the flyover position and three different Mach numbers for the sideline position towards evaluating the effect of the wind tunnel speed variation on the noise produced by the flap model. The first analysis, shown in Figures 77 and 78, provided insight about the Strouhal number scale with velocity variation. The results show the flap noise with baseline and perforated tips scale with Strouhal number in flyover measurements, whereas with rounded, seal and new seal tips, it does not scale. All tips seem to scale with Strouhal number for sideline measurements.

Figure 75: Acoustic spectrum variation for the flyover position obtained at $M = 0.109$ and different angles of attack

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) New seal flap side-edge

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 76: Acoustic spectrum variation for the sideline position obtained at $M = 0.094$ and different angles of attack

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 77: Acoustic spectrum variation for the flyover position at $\alpha = 26^\circ$ and different Mach numbers

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 78: Acoustic spectrum variation for the sideline position at $\alpha = 26^\circ$ and different Mach numbers

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 79: Mach scale factor with Strouhal number for the flyover position at $\alpha = 26^\circ$

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 80: Mach scale factor with Strouhal number for the sideline position at $\alpha = 26^\circ$

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figure 81: Variation in the OASPL with Mach number for flyover and sideline positions at $\alpha = 26^\circ$

(a) Baseline flap side-edge

(b) Rounded flap side-edge

(c) Seal flap side-edge

(d) Seal flap side-edge (perforated)

(e) New seal flap side-edge

(f) New seal flap side-edge (perforated)

Reference: Author

Figures 79 and 80 show the way the Mach scale factor changes in function of the Strouhal number for both flyover and sideline measurements, respectively. A progression of N is observed in Figure 79 between scale with the 6th power for low Strouhal numbers up to $St \approx 200$ and with 8th power for higher Strouhal numbers for both baseline and rounded tips. The N progression in the two seal and two new seal tips occurred between scale with the 6th power for low Strouhal numbers up to $St \approx 100$ and with 4th power for higher Strouhal numbers (Figure 80). Higher fluctuations were influenced by the shear-layer over the edges of the model in both flyover and sideline configurations. The scaling factor is higher than the background noise factor shown in Figure 69, which indicates the higher the flow speed, the higher the Signal to Noise Ratio (SNR).

The overall sound pressure level progression with the Mach number, shown in Figure 81, clearly demonstrates a scale factor between 6 and 8 is present in flyover measurements for the baseline tip, whereas the sideline configuration changes the scale factor to 4. The rounded tip reveals a scale factor near 6 in both positions. Comparisons between flyover and sideline measurements in the two seal and two new seal tips show similar tendencies for scale factor 4. In general, the flyover cases exhibit higher Mach scaling for the overall sound pressure levels probably due to oscillations and high frequency tones in mid to high Strouhal numbers that increased the overall scale factor locally, as shown in Figures 79 and 80.

5.2.8 Effect of tips

The comparison in Figure 28 provides new understanding about the high broadband noise reduction achieved with the use of the rounded, seal and new seal tips in the flyover case, although the tips increase the acoustic spectrum in the sideline position.

Figure 82: Acoustic spectrum variation at $\alpha = 26^\circ$

An important noise reduction in mid to high frequencies was observed for flyover measurements of the three geometries tested (rounded, seal and new seal side-edge tips). The tips produced 5.0, 3.9 and 6.1 *dB* less noise than the baseline flap side-edge, respectively, as shown in Table 16, and increased the noise measured for the flap in the sideline position (Table 17). The switch effect of the noise produced by the tips on both positions in comparison with baseline tip is probably due to the noise radiated by the tested tips in the lateral plane or sideline position, as shown in Figure 83. Negative values mean noise increase.

Table 16: Noise reduction measured for different flap side-edge tips for the flyover position at $\alpha = 26^\circ$ and $M = 0.109$

Flap side-edge tip	Reduction [dB]
Baseline	0
Rounded	5.0
Seal	3.9
New seal	6.1

Reference: Author

Table 17: Noise reduction measured for different flap side-edge tips for the sideline position at $\alpha = 26^\circ$ and $M = 0.094$

Flap side-edge tip	Reduction [dB]
Baseline	0
Rounded	-3.6
Seal	-3.2
New seal	-1.4

Reference: Author

Figure 83: Acoustic spectrum of noise reduction for different flap side-edge tips at $\alpha = 26^\circ$

Reference: Author

5.2.9 Perforation effect

Figure 84 shows the perforation effect on the tips. Regarding the flyover cases, the perforation was more productive for the seal flap side-edge with 6.7 dB than for the new seal flap side-edge with 7.1 dB (71% and 16% less noisy than non-perforated tips, respectively). However, the last configuration was the most efficient flap side-edge tip for noise reduction, as shown in Table 18. The sideline measurement results show the perforated tips keep almost the same level of baseline spectrum at low and mid frequencies (Table 19). Background wind tunnel noise affects mid frequencies flyover results. The noise spectra increase in perforated tips at high frequencies was related to the sound produced by the perforations. Figure 85 also shows the noise reduction acoustic spectrum.

Figure 84: Effect of the perforated flap side-edge tips on far-field noise spectrum at $\alpha = 26^\circ$

Reference: Author

According to Choudhari et al. (2002), the slight noise increase at high frequencies for the two tab configurations was associated with the small-scale fluctuations added to the flow by the tab.

Table 18: Noise reduction measured for different perforated flap side-edge tips for the flyover position at $\alpha = 26^\circ$ and $M = 0.109$

Flap side-edge tip	Reduction [dB]
Baseline	0
Seal	3.9
Seal (perforated)	6.7
New seal	6.1
New seal (perforated)	7.1

Reference: Author

As shown in Figures 86, 87, 88 and 89, further aeroacoustic measurements were taken for the determination of the influence of perforation location on the flap spectrum.

Table 19: Noise reduction measured for different perforated flap side-edge tips for the sideline position at $\alpha = 26^\circ$ and $M = 0.094$

Flap side-edge tip	Reduction [dB]
Baseline	0
Seal	-3.2
Seal (perforated)	0.4
New seal	-1.4
New seal (perforated)	0.4

Reference: Author

Figure 85: Acoustic spectrum noise reduction for perforated flap side-edge tips at $\alpha = 26^\circ$

Reference: Author

Figure 86: Effect of the perforation location on the seal flap side-edge tips at $\alpha = 26^\circ$

Reference: Author

Figure 87: Acoustic spectrum noise reduction for the seal flap side-edge tips at $\alpha = 26^\circ$

Reference: Author

Figure 88: Effect of the perforation location on the new seal flap side-edge tips at $\alpha = 26^\circ$ with one (a and b) and two (c) perforated elements

Reference: Author

For the seal flap side-edge, the acoustic spectrum behavior of the model with the perforated pressure side extension was almost the same of the tip configuration with total perforation in both flyover and sideline cases and showed no relevant acoustic differences (Figures 86 and 87).

The total perforation on the tip for new seal flap side-edge shows a higher noise reduction in comparison with other perforation locations. However, as in the previous configuration, the analysis of only one perforated element revealed the perforated pressure side extension displays the two spectra of lowest noise intensity for flyover and sideline measurements (Figures 88(a), 88(b), 89(a) and 89(b)). The analyses of two perforated elements revealed the combination of the perforated pressure side and leading-edge extensions showed the second spectrum of lowest noise intensity. (Figures 88(c) and 89(c)). Variations in the perforation locations were more visible at low and high frequencies and at mid frequencies, they did not show greater differences.

Figure 89: Acoustic spectrum noise reduction for the new seal flap side-edge tips at $\alpha = 26^\circ$ with one (a and b) and two (c) perforated elements

6 CONCLUSIONS AND RECOMMENDATIONS

Detailed flow measurements were performed in a large-scale flap model in both flyover and sideline positions with four main different side-edge tips, in the LAE-1 wind tunnel at the São Carlos School of Engineering - University of São Paulo (EESC-USP), for the experimental evaluation of the noise reduction from flap side-edge. The investigation determined the aeroacoustics and aerodynamics of the flow-field around the flap side-edge for the understanding of the mechanisms responsible for the noise generation. A perforated material was applied to the flap side-edge in an attempt to reduce the noise and changes in the flow-field with the application of a perforated side-edge were also detected.

A review on the literature on flap noise provided significant information about aircraft/airframe noise sources and flap side-edge noise-generation mechanisms and noise reduction technologies. The aeroacoustic and aerodynamic wind tunnel tests performed were guided by past experimental tests conducted in different facilities. The results agreed with those of the bibliography review, which demonstrates the correct performance of the experimental tests conducted with the flap model.

Flap acoustic noise was investigated by a phased array of microphones and beam-forming techniques. The mean aerodynamic steady features of the flow over the flap model were assessed by chord-wise and span-wise on-surface pressure measurements conducted by pressure taps distributed along the model, and off-surface measurements, as aerodynamic forces, taken by an external three-axis balance and flow characterization by a 7-hole pitot probe. The measurements were performed under different Mach numbers (0.076, 0.085, 0.094, 0.101 and 0.109) and angles of attack ($\alpha = -6^\circ$ or 0° to 30° in 1° , 2° , 5° or 6° steps, depending on the test). The analyses revealed a clear connection between the far-field noise and the aerodynamic behavior of the vortex system generated at the lower and upper edges of the flap tip. The characteristics of the flow-field in the vicinity of the flap tip edges were prominent in relation to the most important sources of airframe aeroacoustic noise.

The aerodynamic flow measurements confirmed the existence of a side-edge vortex which limits the aerodynamic performance. The characteristics of the merged vortex were visualized through the oil-flow visualization technique applied at the flap side-edge face for the determination of the near-field flow. The aeroacoustic measurements provided information on one of the most dominant source mechanisms of flap side-edge noise. The interaction between the flap pressure side vortex and the side-edge surface played a major role in the generation of noise. The vortex size and strength were reduced, which significantly reduced the magnitude of the radiated noise.

A $\alpha = 26^\circ$ flap deflection angle was identified as the most interesting configuration for the compensation of the additional lift produced by the flap with no main wing element. The results of the chord-wise-distributed pressure taps show a suction peak on the upper side-edge surface for the baseline and rounded cases, which indicates the presence of a flap tip vortex that interacts with the flap side-edge surface at $x/c \approx 0.18$. The span-wise pressure taps verified the vortex influences the pressure distribution on both pressure and suction sides from the flap tip ($y/b = 1$) until $y/b = 0.77$. Seal and new seal tips displayed a lower-surface pressure gradient by moving away the vortex system. The force measurements showed the tip treatments alter the overall aerodynamic flap efficiency and increase the maximum lift coefficient, effective aspect ratio, and drag coefficient. The 7-hole pitot probe results (u^* , v^* , w^* and vorticity) and the analyses of the wake and flow mapping evidenced two effects created by the application of different side-edge tips. Firstly, the vortex downstream the flap was shifted from the flap surface. The vorticity strength was then reduced in the flow-field around the flap side-edge, which verified the results addressed in the pressure distribution analysis. The vorticity was reduced by the decrease in some pressure differentials between the suction and pressure surfaces, which produce a weaker vortex with less induced velocities around it.

Modifications in the flap side-edge in flyover position significantly reduced the noise radiated from the vortex system shifting it away from the side-edge surface and reducing their intensity. In general, the noise spectra of the model are dominated predominantly by a broadband component. According to the spectrum results of the analysis of the most prominent noise source per ROI, the side-edge region exerts a strong influence on the total noise, in agreement with the quantitative beamforming source location maps, which showed the main source of noise was located in the leading-edge region. The trip tape used improved the aerodynamic characteristics with a fully developed turbulent boundary layer over the model. No significant effects were observed on the acoustic measurements. The pressure perturbations in the seal flap side-edge showed a maximum of ± 2 dB in all frequency range. Variations in the angle of attack slightly increased the broadband noise at high frequencies for the baseline flap tip in the flyover position, whereas the other tips reversed the behavior decreasing the acoustic spectrum for higher angles of attack ($\alpha = 26^\circ$, 28° and 30°) due to the vortex separation from the flap surface upstream. The increase in the flap deflection angle for the sideline cases decreased the magnitude of the acoustic spectrum. Scaling analyses also revealed the OASLP scales with Mach scale factor $N = 6$ in the flyover baseline and rounded cases and corresponds to a dipole noise source. Seal and new seal tips configurations were consistent with a monopole noise source ($N = 4$) in both positions. Although rounded, seal and new seal tips decreased 5.0, 3.9 and 6.1 dB of the acoustic noise, respectively, for flyover measurements. In comparison with the baseline case, the three main tested tips increased the total noise for the sideline position, which suggests the noise was more efficiently radiated to the lateral flap surface.

Finally, a perforated side-edge was applied to the flap at different perforation locations (leading-edge extension, pressure side extension, tab or total perforation) and exerted two favorable effects on both flap positions. It displaced the vortex from the flap surface due to the transpiration velocity allowed through the perforated material, which reduced the magnitude of the instabilities induced by the flap side-edge vortex and disturbances that interacted with the solid flap surface by moving them away. It also reduced the vorticity magnitude in the turbulent shear layer and the vortex, hence, the magnitude of the instabilities induced by the flap side-edge vortex. Such an application was mostly noticeable due to the reduction in the low and mid frequency broadband noise. The perforated tips drastically reduced the broadband noise in comparison with the baseline side-edge tip. The perforated seal and new seal tips reduced 6.7 and 7.1 *dB* in flyover measurements, respectively, and 0.4 and 0.4 *dB* in the sideline position, respectively, of the overall sound pressure level of the flap model. The background wind tunnel noise need to be reduced in further flap side-edge noise reduction analysis to avoid noise contamination that hampers results in low and mid frequencies. Large-scale perforated noise-reduction devices are in agreement with the implementation of real-scale devices with no scaling tip perforations.

6.1 Recommendations

Apart from the conclusions drawn, some potential noise-identification technologies should be applied to the flap side-edge region.

Computational aeroacoustics are promising as a measure of noise identification. Although computational simulations are costly, simulations on a high-density mesh with adequate equipment can quickly provide reliable results.

Experimental measurements with PIV and hot-film/wire anemometry must be performed in the flap model with different side-edge geometries for validating the computational approach.

PIV is a flow-field laser optical technique for research and diagnostics the flow. It provides instantaneous velocity vector measurements in a cross-section of a flow. The three velocity components are measured and recorded, which results in instantaneous 3D velocity vectors for the whole area of interest. Real-time velocity maps can be obtained by the use of modern digital cameras and specific computing hardware ([DANTEC DYNAMICS, 2018](#)). In PIV, the velocity vectors are obtained from sub-sections of the flow target area through measurements of the movement of particles between two light pulses. The flow is illuminated in a target area by light sheet and the camera lens captures each light pulse in separate image frames. The pixel-by-pixel correlation of the images identifies the common particle displacement and a velocity vector map is obtained through the repetition of the cross-correlation of the whole area over the two image frames captured ([ADRIAN, 1991](#)).

The Hot-Wire Anemometry (HWA) measured the spectral content of the unsteady velocity perturbations in the flow-field inside and outside the wake flow of the model ([BRUUN, 1995](#)). The Hot-Film Anemometry (HFA) provides information on the surface unsteady spectra of the flow-field. The surface hot-film technique is based on the analogy between heat transfer of an electrically heated wire and its skin friction resistance variation ([HASELBACH; NITSCHKE, 1996](#)). Hot-film/wire correlations provide better insight about contributions of each part in comparison with fluctuations perceived by microphones. Measurements by the hot-film/wire anemometer and microphones were compared to noise beamforming spectra and correlations between flow fluctuations in the near-field and far-field noise could be established. Constant Temperature Anemometry (CTA) is one of the measurement techniques used for the study of the turbulent flow. The working principle of the hot-wire/film anemometry is based on the cooling effect of a flow on a heated body ([KING, 1914](#)). The velocity is measured at a specific point and continuous velocity time series are provided for the obtaining of amplitude and time-domain statistics (mean velocity, turbulence intensity, higher-order moments, auto-correlations and power spectra) ([JØRGENSEN, 2002](#)).

6.2 Dissemination

The first analyses of this investigation have been submitted and accepted at the premier international forum for the field of aeroacoustics, the 24th AIAA/CEAS Aeroacoustics Conference and were presented in Atlanta, Georgia, U.S., on June 28th, 2018. The article produced is entitled Experimental Aeroacoustic and Aerodynamic Analysis of a Large-Scale Flap Side-Edge Model ([ACEVEDO et al., 2018](#)).

The comparison between experimental and numerical aeroacoustic results has been submitted and accepted at the 48th International Congress and Exhibition on Noise Control Engineering to be held in Madrid, Spain, on June 17th, 2019. The article produced is entitled Experimental and Numerical Aeroacoustic Analyses of a Large-Scale Flap Side-Edge Model.

A journal paper entitled Experimental and Numerical Aeroacoustic and Aerodynamic Analyses of a Large-Scale Flap Side-Edge Model which includes comparisons between experimental and numerical aeroacoustic and aerodynamic results is currently under review by the AIAA Journal. The flap side-edge numerical investigation was developed at the Laboratory of Aerodynamics of the Aeronautical Engineering Department from São Carlos School of Engineering - University of São Paulo (EESC-USP).

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