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MASTER'S IN AEROSPACE ENGINEERING

Master Thesis

STUDY OF THE AFC TECHNOLOGY DEVELOPMENT: A CASE STUDY APPLICATION IN THE AERONAUTICAL INDUSTRY

Report

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ABSTRACT

The world is going through a constant evolution, where the objectives are much more ambitious than before thanks to the new technologies. However, the focus is no longer on only improving existing services without considering anything else; nowadays, the benefit provided is just as important as the way in which it is achieved, and the main efforts currently are focused on achieving a sustainable world, in which life continues to be as we know it and climatic catastrophes are eradicated, at least those in which human activity is the main cause. That is why this thesis is focused on the implementation in the aeronautical industry of a promising technology called Active Flow Control (AFC).

To that end, an exhaustive state-of-the-art is conducted in which the AFC technology is described in general, to then deep dive in its aeronautical applications. Next, the technology required so as to implement the AFC in an aircraft is described, covering the main elements needed to influence the flow around the aircraft together with the power supply architectures necessary to feed the actuators.

On the other hand, and based on the information previously gathered, a Minimum Viable Product (MVP) is defined, in which AFC technology is to be implemented in an Airbus A-320 aircraft. In the MVP, both the technological elements that need to be installed together with the system infrastructure are established, thus defining the architecture of the product.

In order to ensure the viability and profitability of the MVP, a feasibility study is conducted, analysing the installation of the product from an airline perspective considering three different casuistic: an aircraft that flies only at national level in Spain, an aircraft that flies at international level in Europe and a complete fleet of Airbus A-320 that flies at international level in Europe. The preliminary economic analysis covers the three cases mentioned, and the complete economic figures are presented for the third case, the one with more practical interest.

On the other hand, the regulatory emissions framework currently in place in Europe is described, assessing whether the installation of the MVP in a European airline could influence the overall company strategy towards the 2050 zero net goal achievement. Due to the current situation, in which the global awareness of contaminant gases emissions has increased considerably, all the projects aiming to reduce this type of emissions have a great impact in the industry, and the AFC technology investigations are a good opportunity to improve aeronautical industry contaminant footprint in the world.

Keywords: Active Flow Control, Aerodynamic, Aeronautical Industry, Feasibility Study, Cost Analysis, Airbus A-320.

DECLARATION OF HONOR

I declare that,

the work in this Master Thesis is completely my own work,

no part of this Master Thesis is taken from other people's work without giving them credit,

all references have been clearly cited,

I understand that an infringement of this declaration leaves me subject to the foreseen disciplinary actions by The Universitat Politècnica de Catalunya - BarcelonaTECH.

Title of the Master Thesis: **Study of the development of the AFC Technology: a case study application in the aeronautical industry**

Signed:

Oscar Macía,

June, 22nd 2022

Master in Aerospace Engineering

ACKNOWLEDGMENTS

Life consists of a set of stages which a person goes through – even without considering it, day after day the time is inexorably moving, and it is a must to seize every moment. During the master stage, I have been able to meet incredible people, learn new skills and improve considerably already obtained abilities. If I look behind, six years ago when I started my university studies, I see an amazing evolution both personal and professionally. I was not especially a fan of the aircrafts or the space, I was just curious about how is possible to make an object weighting tones capable of flying or orbiting, among other space related things, and as I said, during these years I have learnt the answers to these questions and many more, and, something I think it is even more important, I have discovered new questions to which look for answer. Therefore, I am proud of the decision I made regarding the university path choice I made.

To begin with, I would like to thank my family and friends for all they have done for me during these last six years. Together we have been through difficult situations and, no matter what or how, we have been able to succeed in all of them. It is important to remark that I am not only talking about difficulties in the studies, but I am referring to life situations that come at you, such as the loss of relatives, or the social distancing due to the different paths that each one follows in his/her own life. Nevertheless, in every moment I felt I could not, they showed me that giving up was not an option, and we managed to keep going, so I want to thank all of you.

The Master Thesis is a project in which is needed to invest a lot of effort, and therefore the topic chosen is a very important decision every student must take. Following this line, I feel incredibly grateful to my two tutors, the director and the co-director of this master thesis, Silvia Rodríguez and Daniel García. I had the pleasure of attending Silvia and Daniel lessons during the bachelor's degree about economic concepts related with engineering, and they have always been a reference for myself on why to follow the economic career path does not have to mean moving away from the world of engineering. There are challenges that must be solved, and being able to relate them to one of the biggest reasons the world moves (money) is of tremendous importance, and they show this to their students year after year. They both have helped me in the guidance of developing this project, and they have shown me that, beyond being great professionals and passionate about engineering projects from the economic point of view, they are great people, and I really hope us to work together in the future again.

To sum up, I want to thank all those people who have always trusted on me, even when I did not, who have always believed and who have projected me directly forward. My heartfelt thanks to all of you.

Oscar Macía Fernández

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1 INTRODUCTION

This first section is aimed to establish the aim, the scope, the requirements and the justification of the study.

1.1 AIM

The main objective of this project is to investigate the possible applications of Active Flow Control (from now on, AFC) technology in the aeronautical industry, proposing a minimum viable product (from now on, MVP) and focusing on the economic study of the proposal.

Firstly, the target will be to assess the different applications of AFC in the aeronautical industry, secondly, the definition of the MVP in a specific aircraft model and thirdly a cost analysis and a feasibility study will be conducted.

1.2 SCOPE

Bibliographic review

- Review and expand the concepts of flow control, focusing on main applications in aeronautical industry.
- Get more familiar with strategies to increase aerodynamic efficiency in aircrafts and high-lift devices.
- Read and understand the different strategies to conduct feasibility and profitability analysis and implement it within the MVP economic study.

Background

- An investigation into the AFC will be performed, with the objective of defining the technology and identifying the different ways this technology can be approached.
- The main components to implement AFC will be described, identifying the different possibilities available in the market to achieve proper implementation of the solution.
- The applications of the AFC technology will be described, thus assessing the benefits that provides to aeronautical industry, aiming to increase aerodynamic efficiency.

Case study: MVP applied to Airbus A-320

- The specific application of AFC will be defined, together with the initial conditions as well as the key results obtained through an aerodynamic study.
- The technological configuration to implement AFC technology will be defined, carrying out an efficiency analysis focused on mass-power cost in such a way the optimum architecture will be selected.
- The final configuration of the MVP will be presented once the objective and the technological architecture is selected, clearly establishing the product to be studied within the economic analysis.

Economic analysis

- A cost analysis will be carried out aiming to establish the price to manufacture the defined configuration to implement the AFC technology in the aircraft.
- To determine if the implementation of the MVP is profitable, a feasibility study will be carried out from different perspectives, considering optimistic, pessimistic, and intermediate scenarios.
- A risk analysis will be conducted to understand the possible consequences that certain situations can bring and the probability that they will occur with the aim of measuring and hedging the risks.

Environmental study

- The main regulations related with carbon emissions in the aeronautical industry will be described, analysing what are the current conditions and the future regulatory framework that is to be established in the upcoming years.
- Carbon credit management will be described, assessing whether they could affect aeronautical industry companies and how this practice can be related with AFC implementation.

Budget

- In order to price the study presented throughout this thesis, a budget will be presented thus considering the hours invested in its development, as well as the associated costs that allow obtaining maximum quality in delivery.

Conclusions and future work

- Future lines of work within the same field will be suggested to go further.

Out of Scope

It is important to note that there are some studies that could be done in the field that this project belongs to, but either because they are not fully focused on the main objective of the project, or due to lack of time, they will not be covered in this thesis.

- Aerodynamical study of the wing efficiency implementing AFC technology.
- Design of the AFC actuators and power supply elements.
- Physical analysis of the impact of number of actuators in the wing.
- Development of algorithms to solve aerodynamic simulations.
- Deep study regarding the AFC aerodynamic efficiency gains.
- Deep study regarding the acoustic benefits of implementing AFC.
- Structural analysis and design of electrical network for AFC configuration implementation.
- Modelling of the MVP in a graphic design software.
- 3D aerodynamic simulation of the AFC implementation in a specific aircraft.

1.3 REQUIREMENTS

First of all, the specific requirements that must be met to complete the study regarding the content of the project are presented:

- General description of the AFC technology, focusing on aeronautical use-cases.
- Definition of the current state-of-the-art regarding AFC technology implementation.
- Presentation of an aerodynamic analytical case study of an application of AFC technology in a particular aircraft.
- Definition of a MVP, including AFC application objective and the technological architecture to be implemented.
- Economical and feasibility study to assess implementation of the MVP in the aeronautical market.
- Presentation of a project budget specifying the hours invested in the development and the additional associated costs.
- Elaboration of environmental impact analysis of the AFC implementation in the industry.

To conclude this section, the requirements that must be met in the project regarding the regulations that govern its development are introduced below:

- Invest a total of, at least, 300 hours in the development of the study.
- Develop all the documentation in British English.
- Deliver the project on 30th June, 2022.

1.4 JUSTIFICATION

The aeronautical sector has spent years taking passengers from one place to another around the world, managing to shorten the time between enormous distances in an incredible way. Every day, approximately 12 million people around the world take an aircraft to travel from one place to another, whether for business, tourism, or other reasons. This means that it is a tremendously attractive market for companies, either for what they generate directly with air transport to the companies of purely aeronautical industry, as well as for all industries that participate in some way in the value chain of this business. Airports, for instance, are a great example of this; they generate +70 million jobs worldwide, contributing +3 billion dollars to the world economy.

Technology does not stop evolving in every way, even managing to open new paths unimaginable just a few decades ago (e.g., metaverse). And as expected, the aeronautical industry is not far behind in this technological evolution. The investment is very aggressive in certain fields, but in recent years it has focused above all on trying to reduce the contamination that exists throughout the world, which continues to grow due to human action and whose consequences have not yet been fully produced. Meteorological catastrophes such as floods, droughts or fires have been occurring in recent years, and dependence on fossil fuels must be reduced if the world we live in is to be sustainable in the long term.

Despite the fact that there are many initiatives aiming to reduce the carbon footprint, in the short term it does not seem that large industries are capable of surviving with their normal operations without the use of fossil fuels. The alternatives are promising, but the reality is that, at the moment, they are not enough reliable to absorb the existing activity. That is why technologies such as active flow control are gaining presence in the current market, since they exactly pursue the objective of reducing contamination by increasing aerodynamic efficiency and allowing flight operations to be developed in their different optimal ranges in relation to consumption.

This thesis focuses on investigating the possibilities of a promising methodology that has been considered in the aeronautical landscape since the beginning of Prandtl's time, but the technology was not developed enough to be profitable. However, today there has been exponential progress in electronics and manufacturing techniques, so if it is ever possible to put this technology into practice, it must be now. The main objective is, therefore, to disentangle the main existing options, to evaluate the technology necessary for its implementation, and to analyse the economic feasibility of the project. The world in which we live needs changes, and technology is the main enabler to improve the future; all resources must be destinated to allow life on this planet to be sustained and sustainable for future generations. What we do today has an impact in eternity.

2 STATE OF THE ART

In order to establish the basis of the background necessary to understand the reasons for carrying out the study presented in this thesis, in this section it is exposed firstly the theoretical framework about AFC needed to develop the analysis conducted during the project, together with the state-of-the-art of AFC implementation in the aeronautical industry and finally the presentation of the different technological components required to provide the desired effect when implementing the AFC architecture solution.

2.1 BACKGROUND

In this section, the details of the AFC technology are explained, that is the definition of the technology, when it was initially raised, the different flow control types currently available, the details around the main components needed and how to be applied in today's environment.

2.1.1 Fundamentals of Active Flow Control technology

Active Flow Control is the on-demand addition of energy into a boundary layer for maintaining, recovering or improving vehicle performance. This technology has the potential to be one of the key contributors to achieving the aeronautic goal of revolutionizing the energy efficiency and environmental compatibility of air transport aircraft. It was first investigated and described a long time ago, when the boundary layer was discovered by Prandtl, considering actuation methods for steady mass transfer via suction or blowing, and unsteady perturbations created by different set of actuators [[3].

It is worth to mention that it has been demonstrated that this technology is capable of improving vehicle performance reducing boundary layer separation and increasing circulation, within wind tunnel experiments. When implemented into an aircraft, the reduction of drag and therefore consuming less fuel during flight operations is achieved by using actuators installed in small control surfaces.

The application of this technology seems to be an important step towards a cleaner aeronautical industry; however, to be achieve a widespread application in the industry it is required to provide reliable, robust and energy-efficient actuators and power supply technology to make the technology implementation a feasible initiative. On the other hand, a great computational effort is needed when modelling and simulating the analytical study of AFC implementation in aircraft, in order to maximize the potential benefits of the system.

When designing an AFC technology implementation case study, it is crucial to define the key objective to be achieved within the overall physics of the system, in order to focus the components on the desired objective of the overall proposal. Some examples of AFC intent may be:

- Delay/advance flow transition in the system.
- Suppress/enhance turbulence in the flow.
- Prevent/promote boundary layer separation around a vehicle surface.

Thus, looking for some of the above listed benefits:

- Drag reduction.
- Lift enhancement.
- Mixing augmentation.
- Heat transfer enhancement.
- Flow-induced noise suppression.

It is important to consider that some of the objectives may be interrelated, and they are not exclusive among their selves, meaning that it is possible to achieve one of them when looking for other type of objective. But also in some cases they may lead to potential conflicts, as the achievement of a particular goal may affect another one. For instance, when it is desired to achieve an improvement in the lift-to-drag ratio, promoting transition will lead to a turbulent boundary layer that is resistant to separation and increased lift is reached at higher angle of incidence. Nonetheless, it should be noted that the viscous draf for a laminar boundary layer can be considerably smaller than for a turbulent layer (near to one order of magnitude smaller in some cases), and therefore the laminar boundary layer is more prone to separation, resulting in a lift-loss and a drag-increasement. As a conclusion, the configuration chosen is strongly related with the objective set at the beginning, meaning that the strategic and conceptualization phase is the key when designing and implementing an AFC technology project.

2.1.2 Classification of Active Flow Control methodologies

Once the AFC technology has been introduced, the next step is to define the different possibilities when implementing and prototyping it. In order to cover the overall scope of flow control technology, the passive control is briefly described in this section.

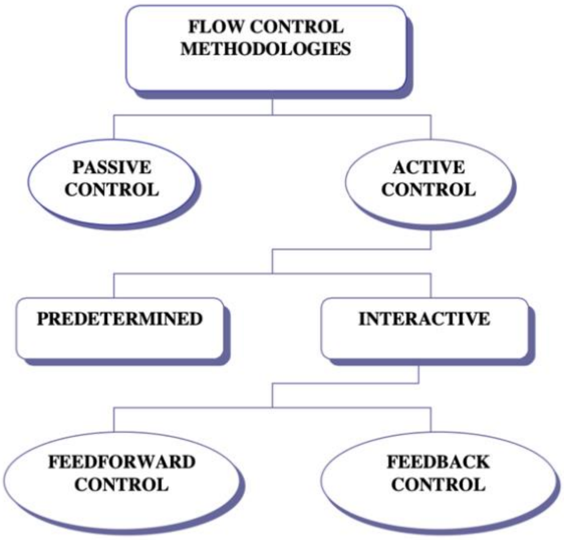


Figure 1. Flow Control methodologies categorization [3]

In Figure 1 the main categories included in flow control methodologies are shown, classifying them based on energy expenditure and the control loop involved in each one.

Flow control involves passive or active devices that provides a beneficial change on the flow flied. The passive methods have been investigated in depth, due to the fact that there is any action required for achieving the improvement in the flow around the specific surface in which the element is installed. Thus, the flow is modified without required external energy addition. In this category, the geometric shaping to manipulate the pressure gradient can be highlighted, together with the use of fixed mechanical vortex generators for separation control and longitudinal grooves or riblets placement on a surface aiming to reduce drag.

However, during the last decade the efforts have been focused on the development of active control methods, the methodology described and investigated within this thesis. In this flow control methodology, energy or auxiliary power is introduced into the flow.

Active flow configurations can be categorized into predetermined or interactive methods:

- A predetermined active flow control scheme involves the introduction of steady or unsteady energy inputs without considering the state of the flow field.
- In an interactive active flow control scheme the power input to the actuator (or controller) is continuously adjusted based on some form of measurement element (sensor).

The second category is very interesting, due to its ability to readjust the actuation implemented in the flow based on measurements conducted in the specific action area, thus achieving a greater control and as a result better improvement in the predefined objective to reach with the AFC application.

The control loop for interactive control can be either a feedforward or feedback loop.

In the feedforward (or open) control loop, the sensor is placed upstream of the actuator. Therefore, the measured flow field parameter and the controlled flow field parameter will differ as flow structures convect over stationary sensors and actuators. It is important to consider that, when this type of control must interact with a specific set of turbulent fluctuations already present in the flow, the open-loop configuration effectiveness is reduced.

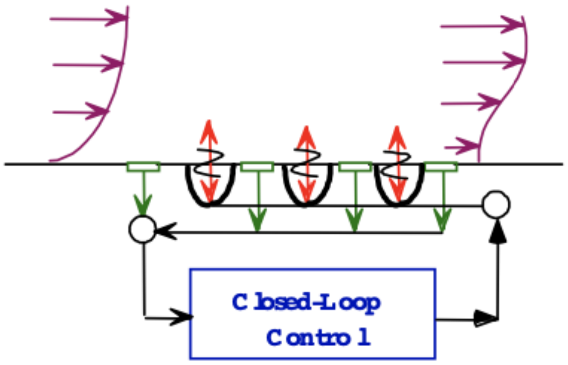


Figure 2. Feedback (or closed) control loop illustration [3]

In the feedback (or closed) control loop, the sensor is placed downstream of the actuator, thus measuring the controlled flow field parameter. The variable controlled is compared with the upstream reference variable, as can be seen in Figure 2.

Feedback flow control involves the triad of flow phenomena, actuators/sensors, and controls as sketched in Figure 3. Typical flow phenomena targeted for application of active flow control are listed along with actuators, sensors and methods of control.

Figure 3. Feedback flow control triad representation [3]

When comparing the two main flow control methodologies existent, it is possible to identify two primary advantages that active flow has, that are not achievable applying passive flow control methodology:

- Active flow control technology leverages and controls a natural stability of the flow to attain a large effect using small, localized energy input. Control is most effective when the control input is introduced locally at a high receptivity region.
- Active control can be used to control complex, dynamical processes like turbulence production in turbulent boundary layers to reduce skin friction, and hence viscous drag, where the reduction is proportional to the surface area covered by the actuators. The correct phasing of the control inputs with respect to the organized flow structures may be the key factor in the success of a control scheme

2.1.3 Active Flow Control technology component

After describing the AFC technology and categorizing it in terms of the different possible configurations available, it is required to define the technological components that are implied when applying an AFC architecture in a proposal. The main components of AFC technology through which the flow modification is achieved are the sensors and the actuators.

As aforementioned, it is required to investigate a lot around these elements, in order to ensure that the technological configuration installed is reliable, robust and energy-efficient. In this section, the sensors and actuators are presented, and in Section 3 the technological configuration of the MVP is defined.

2.1.3.1 Sensors

Flow sensors need to be robust and not significantly alter the flow field that is measured. The usage of sensors when talking about AFC technology is to constantly measure the flow characteristics to provide input to the actuator, and in case needed, send signal to modify the actuation of the architecture elements to ensure the objective of the system is achieved in every single moment of use.

For practical reasons, most flow sensors for active flow control are flush mounted on a solid surface. At the solid surface, typically wall pressure and/or skin friction can be measured. For situations in which the wall pressure is important, there are many devices for measuring pressure fluctuations, which are essentially small microphones. Some examples of sensors include floating element sensors, hot films, and shear stress crystals. In Figure 4 an example of a sensor-actuator system applied to an aeronautical surface is shown.

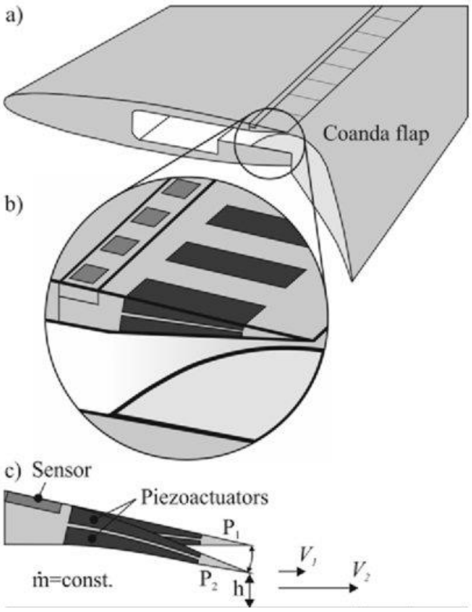


Figure 4. Sensor-actuator system configuration example [15]

2.1.3.2 Actuators

There are many types of actuators that can be used in active flow control. One of the greatest challenges in making active flow control technology practical is the development of robust, reliable actuators. Desired characteristics of actuators include low power consumption, fast response, reliability, and low cost. Four different actuator concepts are highlighted below to give a brief overview of the variety of actuators that can be used in flow control.

The first type of actuator described in this section are the air jet actuators, that impart control through injection of high-momentum fluid into the external flow. There are two different classes of air-jet actuators; the ones with high-authority blowing systems that seek to directly modify the circulation round a lifting body (usually though tangential injection) and the ones with low-authority blowing systems that seek to reduce the effects of flow separation by enhancing boundary-layer mixing. One of the air-jet actuators currently available in the market is named pulsed air jet vortex generators or pulsed jet actuators (PJAs), capable of generating vortices in the boundary layer, with a high-velocity (200–300 m/s) jet of air modulated by operation of a piezoelectric microvalve, with a 40% of energy efficiency.

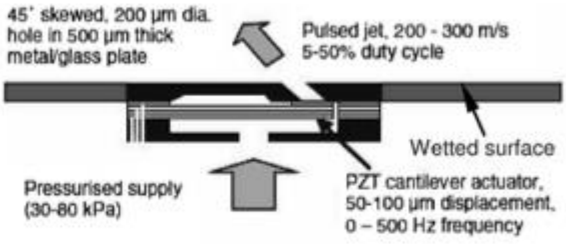


Figure 5. Air-jet actuator illustration [5]

Synthetic jet actuators are a specific type of air jet actuators that use an oscillating mechanical element in a cavity to produce a net momentum flux in an external flow by a process similar to acoustic streaming. Synthetic jet actuators aim to control flow separation by enhancing boundary-layer mixing. Current generation SJAs driven by commercial polycrystalline piezoelectric (PZT) diaphragms can achieve reasonably high levels of authority (peak velocity of 150 m/s), with an electrical-to-fluidic power conversion efficiency of around 10%. However, if the configuration of the diaphragm is single-crystal PZT the efficiency is almost 80%. Thus, it could be expected that actuator efficiency and authority could be doubled by use of bespoke single-crystal PZT diaphragms in the existing actuator designs.

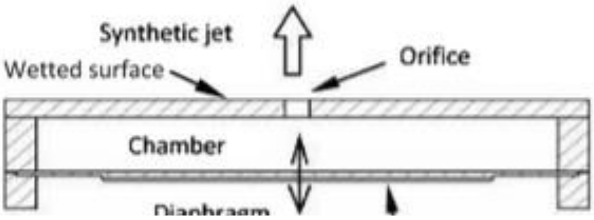


Figure 6. Synthetic-jet actuator illustration [5]

As an alternative configuration to the synthetic jet actuators, the oscillating mechanical element can be a flexible part of the wetted surface, leading to the concept of an active surface or membrane actuator. The main concern when implementing this type of actuator is that there is an impedance mismatch at the actuator–air interface, that limits the achievable peak velocity output to a few meters per second. However, for applications such as transition control, the required actuator velocity is only a few meters per second even at cruise Mach numbers; therefore, the low authority of integral surface devices in absolute terms may not be an issue if the objective is properly selected.

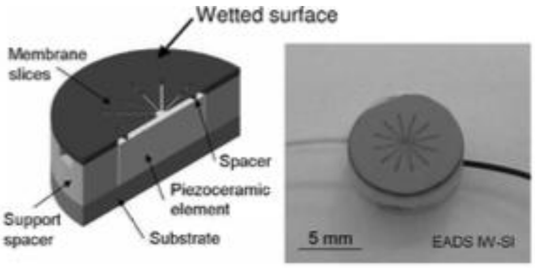


Figure 7. Membrane actuator illustration [5]

The last type of actuator described in this section is the plasma actuator. These devices produce fluidic actuation by ionization and subsequent acceleration of the air local to the actuator. This transduction process tends to be very inefficient (less than 0.1% electrical-to-fluidic energy conversion efficiency). In practice, actuator authority is relatively low (peak velocities of the order of a few meters per second). Therefore, plasma actuators are a potential candidate for applications in which low authority is requested (similarly to what happens with membrane actuators); for instance, turbulent skin-friction drag reduction. On the other hand, it should be noted that plasma actuators have a unique advantage, which is that no moving parts are required during the transduction process, thus representing a significant advantage when it comes to maintenance procedures.

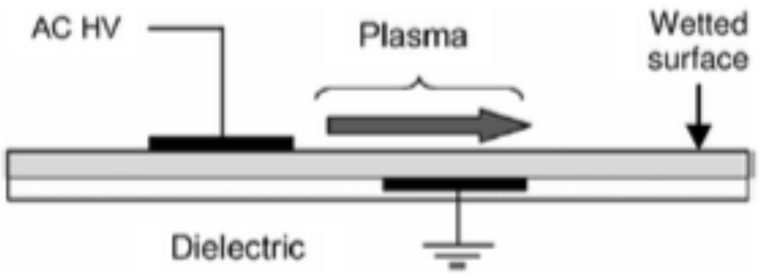


Figure 8. Plasma actuator illustration [5]

2.1.3.3 Power supply methodologies

While there has been some progress toward identifying suitable fluidic actuator concepts for application of AFC on commercial transport aircraft, there is still considerable uncertainty as to the nature of the systems architectures that are needed to support the generation, management, and distribution of power to these actuators. In particular, the choice between distributing power electrically or pneumatically is still an open question, despite significant historical development of boundary-layer control technologies using compressed air and progress toward the development of the more electric aircraft.

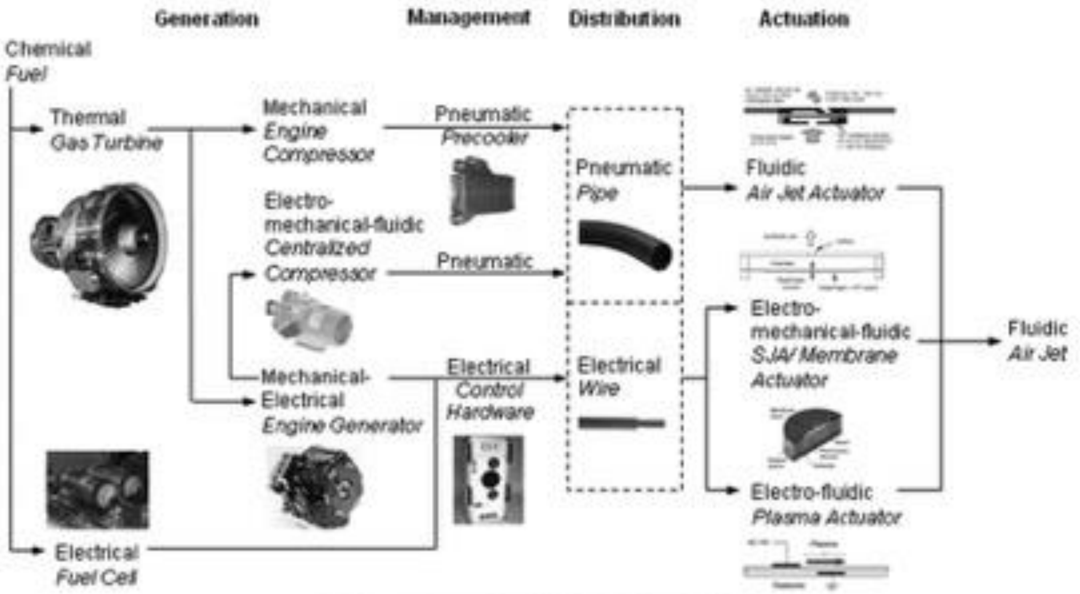


Figure 9. Flow control system architectures [5]

For pneumatic flow control technologies, compressed air is needed at the point of delivery at the actuator; hence, direct bleed of compressed air from an engine initially appears to provide a very competitive power option. However, there are issues in that the amount of bleed air available is correlated with the engine throttle setting, which may severely limit bleed availability at low-throttle conditions: e.g., landing. Furthermore, the pipework required for ducting compressed air is relatively heavy, compared to a system for delivering the same amount of power electrically, and there are significant maintenance costs associated with pressurized systems with many joints.

For electric solutions, an engine-mounted generator is used to generate electrical power, which is then distributed using wires. However, electrical power has to be converted back into the fluidic domain at the actuator through some form of electromechanical- fluidic transduction. The additional conversion steps involved in electrical power generation and distribution for fluidic flow control actuators means that it takes considerable engineering effort to design electrical generation/distribution/conversion systems that match the mass efficiency of pneumatic-only systems. That said, mass reduction and efficiency of electrical machines and digital power systems continues to improve, while there seems to be little scope for similar improvement in pneumatic systems. Therefore, it is likely that the balance will shift further toward electric power generation and distribution for flow control systems in the future.

2.2 AFC APPLIED TO AERONAUTICAL INDUSTRY

In this section the active flow control possible applications in the aeronautical industry are presented. As aforementioned, there are many different possible objectives to look for when designing an AFC proposal, but this paper is focused on the main applications that currently are being investigated in the industry.

There are several basic questions that need to be answered when designing an active flow control technology application:

- Control objective to be achieved needs to be specified.
- Flow phenomenon to be controlled should be defined.
- The physics of the flow should be assessed since it is key to scale and determine influential parameters.
- An appropriate actuation strategy is then selected.
- The range of operation for the key control parameters needs to be determined.

Several recent successful applications of active flow control are highlighted. The review is intended to provide the main cases that are concentrating the most promising research in recent years are described below. The cases described include separation control over airfoils, thrust vectoring, control of flow-induced cavity resonance and electromagnetic turbulence control.

2.2.1 Separation control over airfoils

Active manipulation of separated flows over airfoils at moderate and high angles of attack has been the focus of a lot of investigations and studies during many years, aiming to improve the aerodynamic performance and extend the flight envelope by inducing complete or partial flow reattachment. This reattachment is normally affected by exploiting the receptivity to external excitation of the separating shear layer, which affects the evolution of the ensuing vortical structures and their interactions with the boundary layer. It should be highlighted that the possibility of changing lift without changing angle of attack of flap deflection is beneficial in many areas, and the prevention of separation together with the generation of high lift is an important aspect of this active flow control methodology.

Active flow control investigations for separation control on an airfoil have been analysed from different perspectives using different actuator configurations and strategies, such as external and internal acoustic excitation, vibrating mechanical flaps or steady and unsteady blowing. This area is especially interesting due to the potential it has demonstrated in several investigations, and the benefits presented are very encouraging. When it comes to blowing methodology, it has been demonstrated that separation can be delayed more efficiently by applying oscillatory systems rather than steady blowing. It is achieved in both cases by installing pulsed jets, and the oscillatory blowing required one or two orders of magnitude smaller amount of momentum to achieve comparable gains as steady blowing methodology. The improvements in lift are caused by both attaching the flow to the surface and eliminating a large wake region existing above the attached flow when the steady blowing is weak.

Other investigations have been conducted in the post-stall flow control field, showing beneficial effects of oscillatory blowing in lift enhancement. The lift enhancement is due to large-scale vortical structures convecting over the suction surface that provide a lower average pressure than in the unforced case. As a result, the flow is more attached than in the case without forcing but separated regions still in place.

In recent investigations conducted, the active flow control technology has been demonstrated also at high Reynolds numbers, corresponding to take-off conditions obtaining similar trends when it comes to lift conditions improvement. It can be extracted from some analysis developed that form drag is the main cause of the increase in drag for separated flows. Most of the drag for this particular case is caused by the stalled flap, which at all angles of attack is separated.

On the other hand, compressibility effects on post-stall lift enhancement at flight Reynolds numbers have been also analysed. It is well known that high lift is rarely needed at transonic speeds, since the aircraft wings are constructed to meet take-off requirements. Nonetheless, active separation control at compressible speeds can be applied so as to delay the onset and alleviate the effects of buffet.

This methodology can be also present benefits to rotary wing aircraft, aiming to rapidly change lift and drag values by implementing active flow control with jets at transonic speeds. Oscillatory blowing modifies the shock intensity and location when introduced slightly upstream of the shock. In some cases, the relative lift to drag ratio have been increased by 35% nearly linearly with increased oscillatory blowing.

By implementing synthetic jet actuators, it is also possible to achieve control separation over cylindrical bodies and airfoils. For instance, by allocating a synthetic jet near the leading edge of a thick airfoil, the separated layer present on the upper surface to the airfoil is reattached. It should be noted that the excitation is required to be unsteady with no net mass addition to the flow, due to the nature of the synthetic jet. The results obtained were very promising, presenting a lift coefficient more than doubled and a drag coefficient reduced by a factor of two.

2.2.2 Thrust vectoring

The mechanical systems currently available for implementing thrust vectoring techniques present a high complexity in terms of components to be installed, accounting for as much as 30% of the weight of jet engines in some cases and significantly increasing the cost. Fluidic jet control provides an alternative approach to control the aerodynamic flow of the jet for fixed nozzle geometry. These devices are potentially attractive for shear flow control due to diverse factors:

- System without any moving parts.
- Excitation produced controllable in frequency, amplitude and phase.
- Configuration able to operate in harsh thermal environments.
- System not susceptible to electromagnetic interferences.
- Controlling system easy to be integrated into functioning devices.

A fluidic jet control effective methodology has been investigated in the begging of the decade, in which a synthetic jet actuator is placed adjacent to the exit plane of a high aspect ratio rectangular primary jet. The vectoring results from the synthetic jet drawing fluid from the primary jet conduit. The flow near the top of the duct accelerated and at the same time the pressure along the top is reduced, resulting in a vertical pressure gradient in the duct.

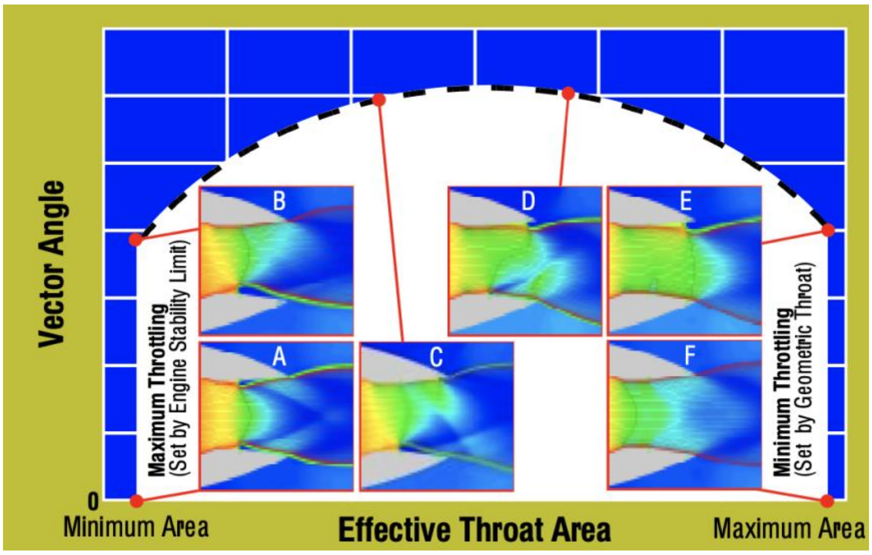


Figure 10. Fluidic thrust vectoring simulation [5]

The fundamental factor to be considered in order to control and effectively decouple thrust vectoring from throat area control (throttling) in the fully fixed nozzle is to vary the injector flow split. At minimum effective throat area, an unvectored condition is achieved by injecting a symmetric distribution of mass flow at the throat (A in Figure 10). By injecting on one side of the throat, it is possible to vector thrust, by setting up an asymmetric flow field (B in Figure 10).

By redistributing an injection mass flow from the throat to the divergent flap on the opposing wall, it is possible to vector the nozzle stream at moderate effective throat areas (C and D in Figure 10). When all the injected mass flow is moved to the flap, the largest effective throat area is produced (E in Figure 10). To achieve a non-vectored condition at maximum effective throat area, the injected mass flow is turned off (F in Figure 10).

2.2.3 Control of flow-induced cavity resonance

Cavity flow analysis is very important for various specific regions of different type of vehicles, such as landing gear and weapon bays in aircraft to flow over ground vehicles. For instance, a case study that can be highlighted in this field is the suppression of flow-induced cavity oscillations, and it should be noted that is not an easy field of study; cavity flows are characterized for presenting a complex feedback process. Convective instabilities grow until reaching saturation in a shear layer, impinging near the downstream corner of the cavity thus generating disturbances that go upstream to the separation edge and, as a result, some disturbance energy is converted into an instability wave at the upstream separation edge, generating large amplitude frequency tones around the cavity. The large sound pressure levels induce significant vibrations that can detriment the contents of the cavity.

The active flow control methodology applied to reduce the previously described effect is achieved by installing a piezoelectric unimorph actuator with an active flap constructed at the upstream separation edge. An open-loop control applied in a deep cavity (L/D=0.5) has been simulated, reducing the sound pressure levels from 144 to 126 dB, the peek in the amplitude spectrum at 230 Hz is reduced almost 23 dB at the expense of raising the level at the excitation frequency approximately 15 dB.

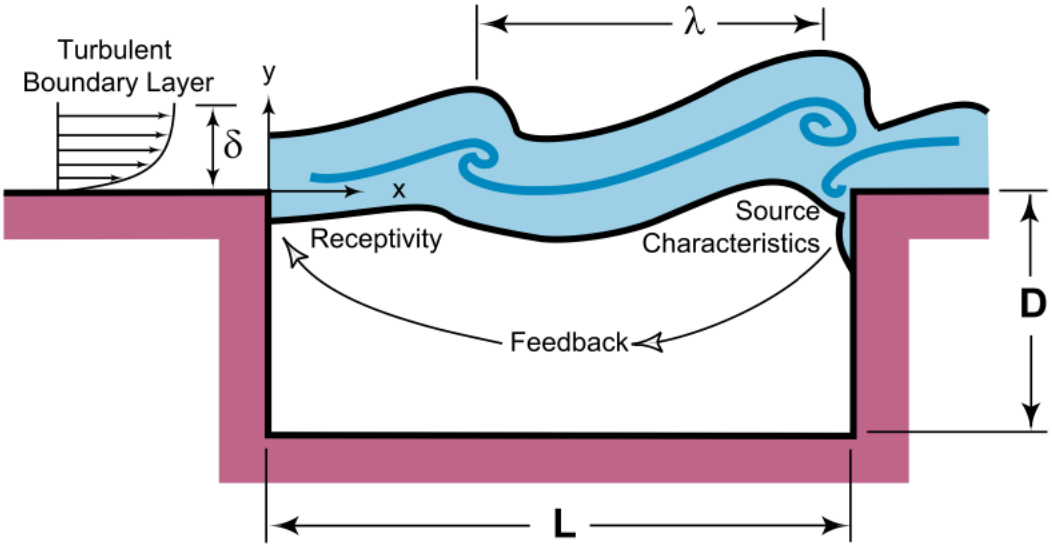


Figure 11. Cavity flow control methodology illustration [5]

If a feedback control loop is applied, the actuators are activated at a higher power level during small pulses and the power input to the actuators is after reduced when the system is under control. As a result, the closed-loop control configuration requires an order of magnitude less in terms of power when compared to the open-loop control configuration implementation.

2.2.4 Electromagnetic turbulence control

The previously described active flow control applications are part of the AFC technology that leverages and controls a natural stability of the flow. There is a second category of active flow control that modifies and controls complex processes, such as for example turbulence production.

Electromagnetic turbulence control is a method of active flow control in which body forces are introduced aiming to influence a large fraction of the boundary layer of the fluid, thus allowing more global control than previous described techniques.

The results obtained in some experiments using this methodology shown that with the usage of a specific electromagnetic force distribution the viscous drag can be reduced as much as 90%. What is more, the possibilities when changing the structure of the boundary layer can be much broader, but this methodology has yet to be fully understood to reach such incredible gain. In this case, the overall Lorentz force is directed normal to the surface, but as mentioned, the response of laminar and turbulent boundary layers to electromagnetic forces is under investigation.

Laminar flow experiments have been conducted in a uniformly conducting fluid, with a configuration of sixteen Lorentz-force actuators in the streamwise direction and four in the periodic spanwise direction, with the magnets oriented spanwise to the flow direction. This analysis have been conducted in both ways, that is as an experiment and as a simulation case study, and when comparing the results obtained from both methodologies it can be observed that a periodic structure with rotational character is shown, with similar velocity profiles obtained in both cases. It should be noted that both methodologies shown to be very sensitive to hitting the resonance frequency for reinforcement of the structures.

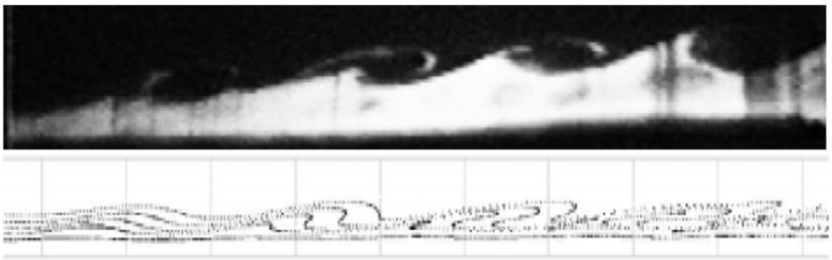


Figure 12. Electromagnetic turbulence control simulation [5]

In Figure 12 the simulations obtained are shown, and it is possible to observe rotational structures in a thickening boundary layer. The magnet orientation strongly affects the flow, due to the difference in Lorentz force strength and distribution in the streamwise versus the spanwise direction. Also, some areas of increased and reduced skin friction can be visualized in the simulations obtained. In laminar cases the agreement between experimental and analytical simulation is considerably high, and proper trends of velocity profiles are obtained. On the other hand, in turbulent cases the simulation presented smaller effects in the skin friction and drag changes than the obtained experimentally.

As aforementioned, additional experiments and simulations are required in this field to better understand the possible applications of this AFC methodology, but it has shown to have a lot of potential for drag reduction purposes when applied in aeronautical surfaces.

3 CASE STUDY: MVP APPLIED TO AIRCRAFT AIRBUS A320

In this section the definition of the case study to be developed is presented, based on the information previously described in the state-of-the-art section. As aforementioned, the objective of this thesis is to develop an MVP that applies a specific methodology of active flow control in the aeronautical industry, to later carry out the economic and feasibility analysis of the proposal. In this section therefore, the main physical target of the AFC technology implementation is defined, as well as the technological configuration to be implemented, which includes actuators and power supply system selection based on studies in which the possible options to be implemented are compared.

3.1 PHYSICAL TARGET OF THE AFC IMPLEMENTATION

The different operations of an aircraft's flight are under constant investigation so as to optimize them, with the aim of reducing drag and increasing the lift produced by the aerodynamic elements installed in the vehicles. The ultimate result is to consume as little fuel as possible, while reducing at the same time the environmental impact caused by air transport. And among all the phases of a flight, take-off and landing operations are those that arouses the most interest nowadays.

The application of AFC for high-lift multi-element wing sections is a field in which a lot of investigations are being currently done. In this section, a specific case study is described in order to set the conditions and major gains obtained when applying AFC methodology to a particular situation.

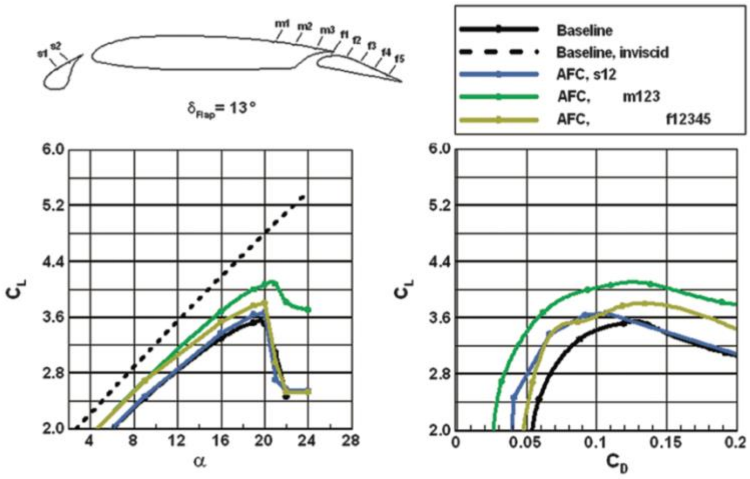
Concretely, a computational fluid dynamics procedure is applied to simulate the interactive flow in conjunction with distributed flow control. As key result, it can be already established that favourable nonlinear interactions using AFC on a conventional wing section and an advanced airfoil led to major aerodynamic performance improvements at representative take-off and landing conditions, thus demonstrating that judicious application of this technology may lead in substantial gains in maximum lift obtained for these operations [[12].

Again, the importance of building robust and efficient technological configurations to apply AFC technology in aeronautical industry should be noted, since the question of whether AFC could be integrated into a practical airplane design is still outstanding. Being able to produce superior high-lift capabilities is a key objective at take-off and landing operations, and every single progress on this matter needs to be carefully analysed and investigated from an airframe manufacturing point of view. On the other hand, computational fluid dynamics simulations and modelling is especially important in these types of studies, and due to the latest improvements in terms of computational capacity, it is possible to obtain much more trustable results.

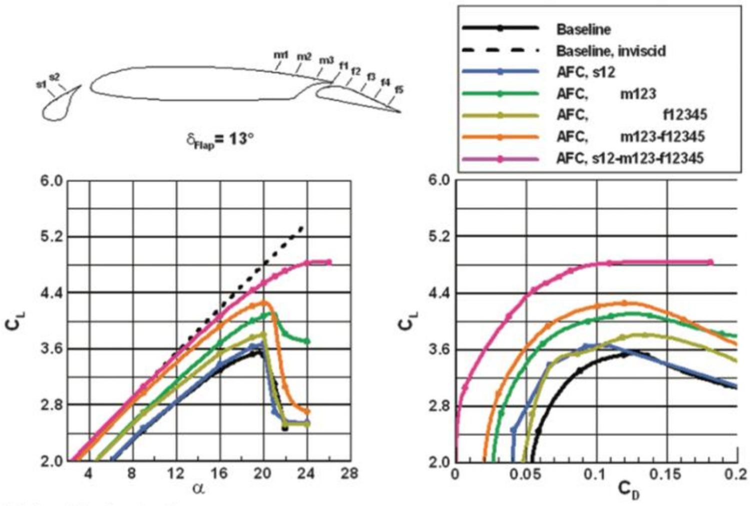
When it comes to the conditions of the source study described in this section, the AFC actuation is achieved with a set of actuators placed on the upper surfaces of the main wing segment and on the movable elements. The actuators are embedded within the respective airfoil elements and are represented by nozzles with constant cross-sectional width of 0.2% airfoil chord. In terms of the jets, they are considered in the simulation by prescribing time-varying dynamic and thermodynamic properties of the fluid at the base of the ports. Zero-mass-flow actuation is defined by sinusoidal pulsation of 20 Hz with a maximum Mach number of 0.242 for all ports. In all the simulations out-of-phase actuation is applied at adjacent ports.

3.1.1 Analysis 1: Take-off configuration with Delta-Flap of 13º

In this subsection the results obtained for the take-off configuration with a Delta-Flap of 13º are presented. The freestream Mach number is 0.1 and the chord Reynolds number is 3 million. For this Mach number the slot momentum coefficient is 0.015. Of the various flow control modes, the actuation on the main element is notably effective with a CL-max near to 4:1 (compared to 3.5 for the baseline). This actuation energizes the nearly separated flow of the main segment and provides added lift. Equally important are favourable effects on the other elements; the extra lift on the main element induces added circulation on the slat and the smaller main wake reduces the displacement effect on the flap. Flap actuation affects the global circulation resulting in added lift on all elements, but it is less effective than the main element actuation at higher angles of attack. Finally, slat actuation results to be ineffectual.



a) Actuation at individual wing components



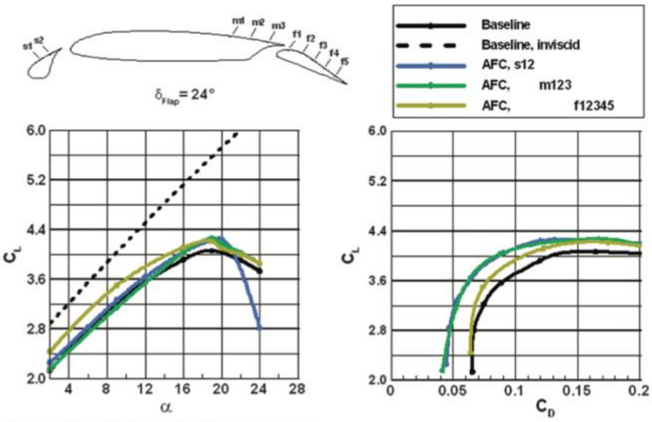
b) Combined actuation

Figure 13. AFC Case study: take-off configuration with Delta-Flap of 13º [12]

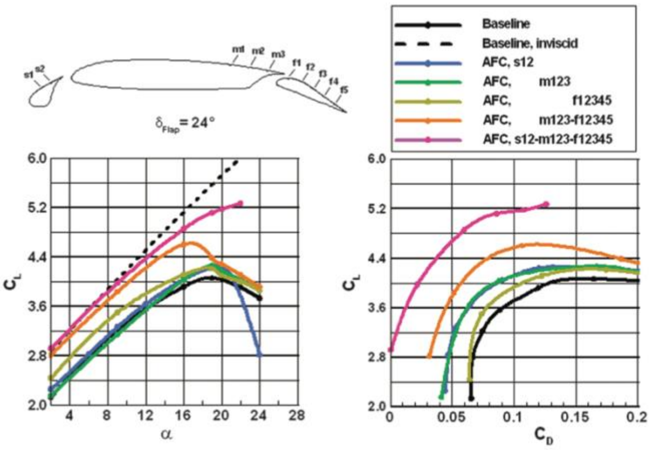
When flow control is applied to both the main and flap elements the gains are relevant. In Figure 13, the lift gain is nearly linear over the range of angles of attack. Slat actuation has a profound impact on the stall characteristics when used in conjunction with control on the main and flap elements. The actuation at the slat produces a smaller wake, therefore the slat wake traverses the adverse pressure gradient regions of the main and flap without significant degradation in flow quality (i.e., less tendency for off- surface flow reversal). The streamlining effect is significant, resulting in larger turning angle in the aft airfoil portion. This actuation augments CL-max by more than 37%.

3.1.2 Analysis 2: Take-off configuration with Delta-Flap of 24º

In this subsection the results obtained for the take-off configuration with a Delta-Flap of 24º are presented. The 24º flap deflection, which represents an additional take-off setting, is shown in Figure 14. According to Figure 14 (a), among the AFC applications at the individual elements the flap actuation is the most effective, providing delta CL equal to 0.25 over the linear range of angles of attack. This implies that the performance of the baseline airfoil is limited by the flap and that the actuation helps improve the flow in its vicinity, resulting also in higher circulation on the flap, influencing the global flow and augmenting the circulation on the main segment.



a) Actuation at individual wing components



b) Combined actuation

Figure 14. AFC Case study: take-off configuration with Delta-Flap of 24º (1/2) [12]

With flap actuation, it is quite likely that the performance limiting factor shifted elsewhere on the airfoil. In order to further improve lift characteristics, flow control on the main element is applied in combination with flap actuation, obtaining very effective results. Contrary to the lower flap deflection, substantial nonlinear lift augmentation is realized as indicated in Figure 14 (b). The performance limiting factor of this case is limited by the flow on the main segment. Consequently, the flow is considerably improved by adding main element actuation. The continual momentum injection supplied energizes the retarded viscous layer in the aft portion of the main element and boosts the load over the entire segment.

As the last case analysed in this subset, flow control on the slat is applied in conjunction with main element and flap actuation, resulting in a relevant impact on the stall characteristics with significant increment in CL-max. The flow control mechanism due to actuation is examined in Figure 15, showing the total pressure fields and profiles at select cuts for the baseline and the AFC application at an angle of attack of 19º. At this incidence the baseline flow is on the verge of separation at the trailing edge of the slat and in the aft portion of the main element.

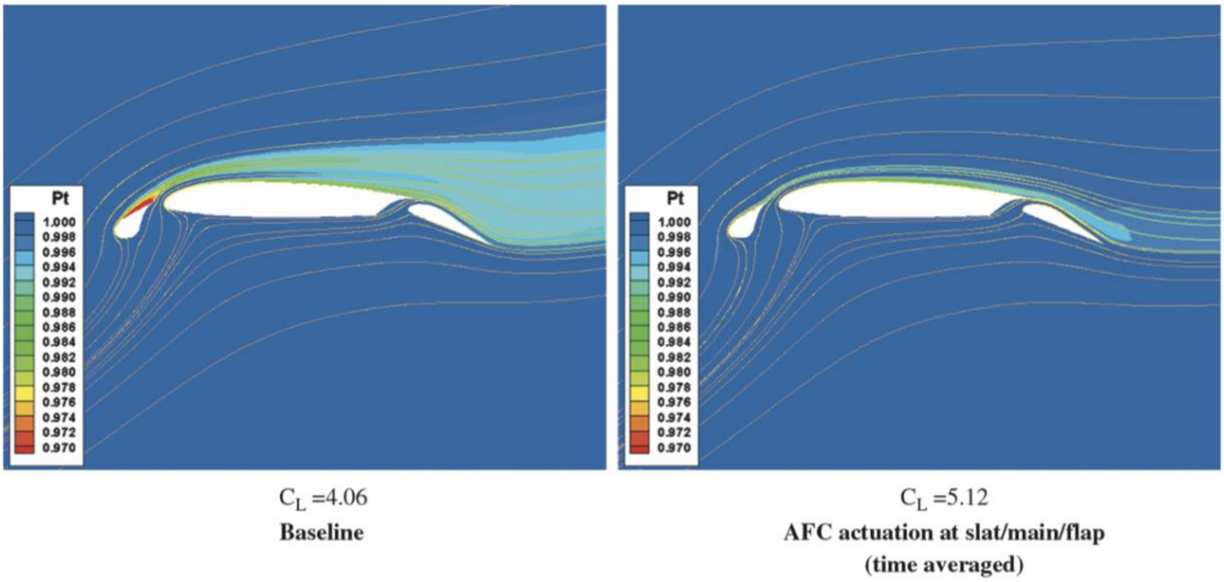
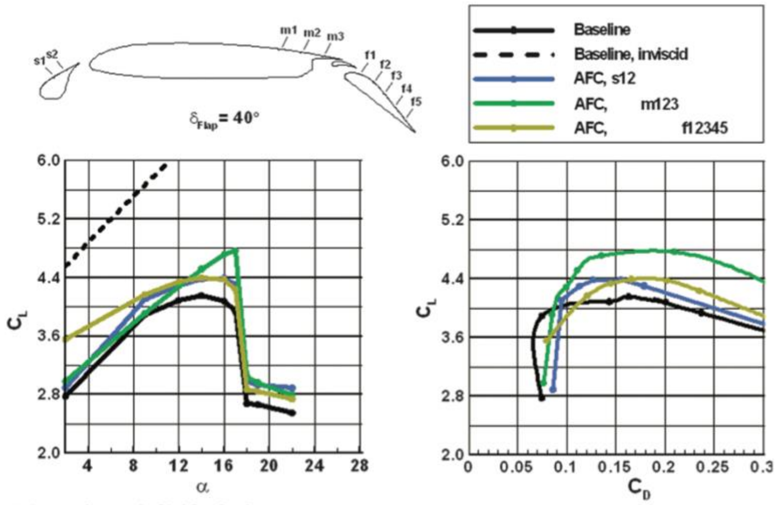


Figure 15. AFC Case study: take-off configuration with Delta-Flap of 24º (2/2) [12]

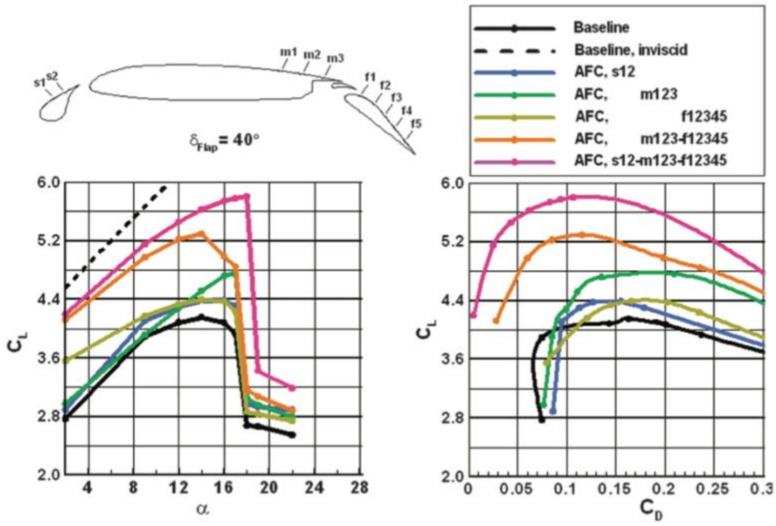
The solutions indicate that the actuation at the slat reduces the size of its wake considerably. Therefore, the slat wake traverses the adverse pressure gradient regions of the main and flap without significant degradation in flow quality. This results in lesser tendency for off surface flow reversal, streamlined flow around the flap, and higher circulation (AFC results in approximately 50% reduction in drag).

3.1.3 Analysis 3: Landing configuration with Delta-Flap of 40º

In this subsection the results obtained for the landing configuration with a Delta-Flap of 40º are presented. The AFC application at the main element is notable at high angles of attack, resulting in sizeable CL-max improvement. In terms of the viscous layer, in the baseline case is separated in the trailing-edge region of the main element and off the flap surface. When comparing it with the results obtained for the case in which the AFC methodology is applied, the boundary layer presents a better behaviour, being much more attached to the flap surface.



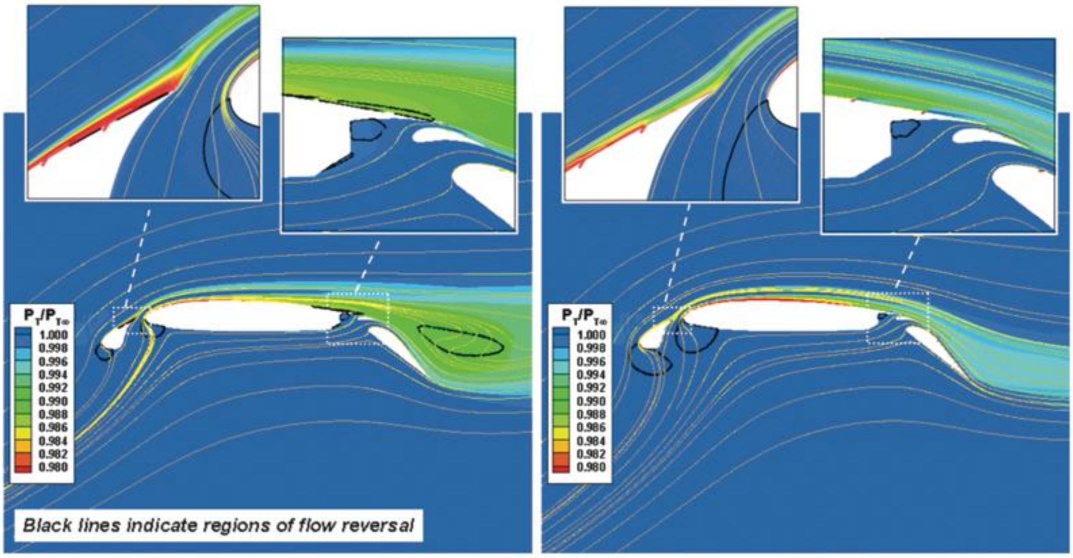
a) Actuation at individual wing components



b) Combined actuation

Figure 16. AFC Case study: landing configuration with Delta-Flap of 40º (1/2) [12]

The ensuing wake off the main element is narrower and it has smaller velocity deficit. Therefore, the flow is able to better sustain the adverse pressure gradient across the flap and higher flow turning results in added circulation. Full actuation of the AFC actuators eliminates the off-surface separation bubble and provides streamlined flow even on the highly deflected flap.



C_L =3.94
Baseline

C_L =5.78
AFC actuation at slat/main/flap (time averaged)

Figure 17. AFC Case study: landing configuration with Delta-Flap of 40º (2/2) [12]

3.2 TECHNOLOGICAL CONFIGURATION

In this section, the technological configuration to be implemented in the AFC technology design of the MVP is described. To define the best possible configuration that suits both the physical objective previously set together with the power supply characteristics of an aircraft, an analysis in which the different possible options are compared is presented. It should be noted that, in order to focus the study on a specific case, the Airbus A-320 model has been selected as the reference aircraft type in which the MVP is to be implemented. The overall aircraft power systems architecture is a series of interacting systems, including power generation systems, transformation systems, distribution systems and power consumption systems, and all of them are interconnected via exchanged energy.

It is proposed to classify AFC systems architectures in a similar manner to the aircraft power systems architecture. It should be noted that the architecture is defined as the combination of an actuator technology and the power supply devices. An AFC systems architecture specifically consists of generation, management, distribution, and actuator systems. The actuator type is known a priori, and thus consideration of the different actuator systems will allow for different distribution systems to be defined.

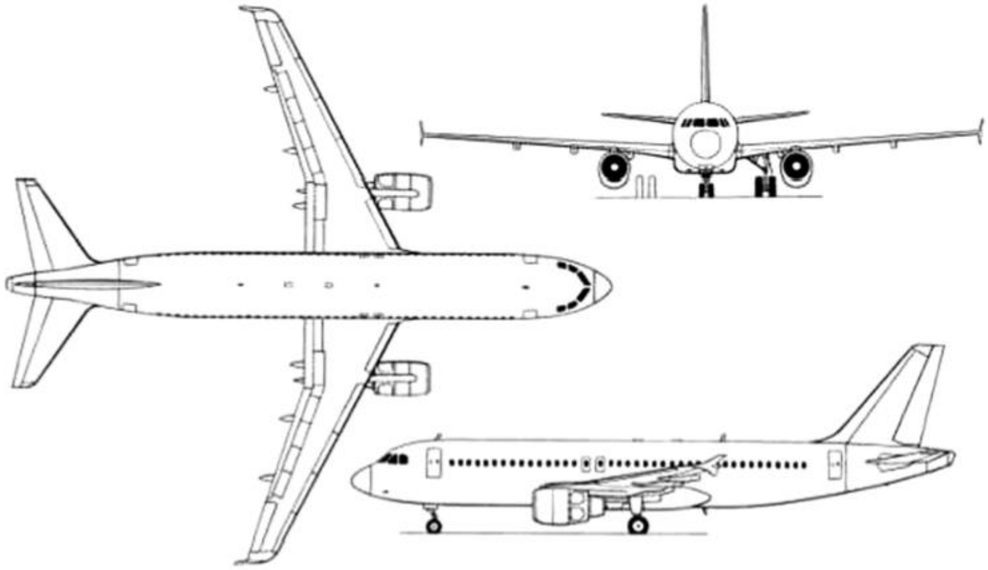


Figure 18. Airbus A-320 civil transport aircraft [17]

Therefore, in this section the effect of actuator selection and associated power systems architecture is analysed with respect to mass cost and power consumption of implementing AFC systems on civil transportation aircraft. This information will be used to decide which is the architecture implemented in the practical case presented in this thesis, and therefore the reference aircraft is again the Airbus A320. If the reader is interested in the details of the calculations here mentioned, the information is available in [[13].

The key system in terms of overall aircraft design is the distribution system, which connects the generation system to the actuator system. The distribution system may be pneumatic, electric, or some combination of the two. Pneumatic distribution gives rise to direct bleed-based flow control, in which compressed air can be used to directly power air jet actuators. Hot bleed air piped from the engine offtake requires power management in the form of precooling before passage to the actuator plenums. Electric distribution is required for SJAs, membrane actuators, and plasma actuators. The IDG for an Airbus A320 supplies 115 VAC, 400 Hz, three-phase power, what has a good advantage when compared with a 50/60 Hz system; that is, the power generation systems are smaller and lighter. An alternative is a hybrid approach that uses both electric and pneumatic distribution. This solution uses one or more electrically driven air compressors to generate compressed air locally to the AFC actuators. The actuators themselves are identical to those considered for pneumatic systems (i.e., air jet actuators). The advantage over native pneumatic systems is that engine bleed air is not required, and therefore it may be possible to provide the required flow control effectiveness at low engine throttle settings, assuming that generator power is available.

Results from this study show that electrical power distribution has clear benefits over pneumatic power distribution for AFC applications in terms of reduced mass, higher overall efficiency, and reduced installed volume for the same power transmitted. The mass cost of transmitting 5 kW of power pneumatically is approximately 2 orders of magnitude greater than doing so electrically. These findings are consistent with the perceived move toward the more electric aircraft concept. In particular, decentralization of pneumatic FC systems is in line with future expectations for decentralization of fluidic systems.

The power-specific mass for the native pneumatic system is estimated to be 5 kg/kW: that is, 5 kg of system hardware required per 1 kW of power flow through that system. For the hybrid system, the overall power-specific mass cost is approximately 6 kg/kW. The mass cost of electric power distribution is shown to be considerably less than that for pneumatic systems (up to 2 orders of magnitude smaller), with added benefits of higher efficiency and smaller volume installation requirements for a given level of power transmission.

Based on previous results, it is concluded that the structure that best suits the requirements to achieve the predefined AFC objective is to implement synthetic jet actuators with an electric power distribution architecture.

The AFC actuation designed for the MVP is accomplished with a set of actuators placed on the upper surfaces of the main wing segment and on the movable elements. The port layouts for the two systems are schematically shown in Figure 19. A set of 10 ports has been used for the conventional section with 2, 3, and 5 ports on the slat, the main, and the flap elements, respectively. The ports are placed in the aft portion of the slat and main elements and five actuators are mounted at equal intervals within the flap. The actuators are positioned such that their respective orifice axes form a 20º angle relative to the local upper surface.

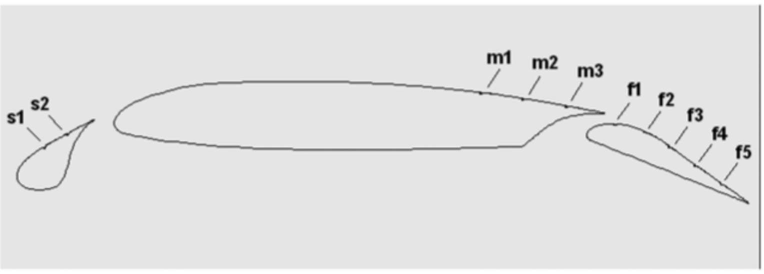


Figure 19. Aerofoil AFC actuators distribution for take-off and landing operations [12]

When it comes to select the AFC actuators distribution in the whole wing to be considered in the MVP, based on the information described in previous sections, the selected system is composed by synthetic jet actuators with an electric power distribution and in a (2,3,5) port configuration placed in the whole aircraft as shown in Figure 20.

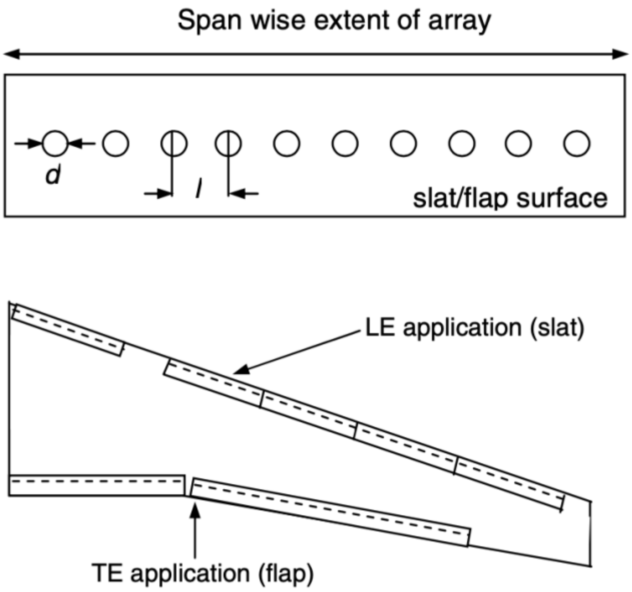


Figure 20. Wing AFC actuators distribution to be implemented in the MVP[13]

It is important to note that there are two possible approaches: to use a unique energy source unit to distribute the power to all the subsystems, or to implement different smaller energy sources. In Figure 21 both options are sketched:

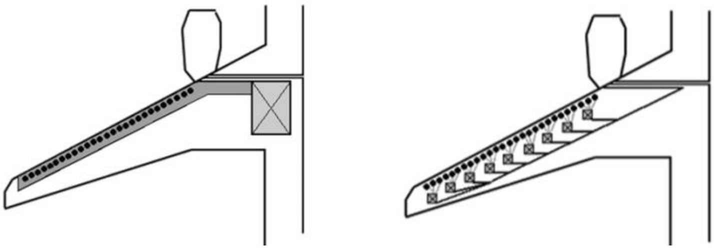


Figure 21. Macroscale and mesoscale power supply systems [13]

In this case, the second approach is followed, so as to ensure reliability of the system by providing redundant systems. It is important to consider that this approach also simplifies the system certification process.

4 ENVIRONMENTAL ANALYSIS

In this section, the main regulations related with carbon emissions in the aeronautical industry are presented, analysing what are the current conditions and the future regulatory framework that is to be established in the upcoming years. On the other hand, carbon credit management is presented, assessing whether they could affect aeronautical industry companies and how this practice can be related with AFC implementation [[23].

4.1 EUROPE AERONAUTICAL EMISSIONS REGULATORY FRAMEWORK

Aviation is one of the fastest-growing sources of greenhouse gas emissions. The European Union is taking action to reduce emissions produced by air transport industry in Europe and working with the international community to develop measures on a global scope.

On July 2021, the European Commission adopted several legislative proposals defining how to achieve climate neutrality in the EU by 2050 in this industry, including an intermediate objective of at least a 55% net reduction in greenhouse gas emissions by 2030. The package proposes to revise several pieces of EU climate legislation, including the EU ETS, Effort Sharing Regulation, transport and land use legislation, setting out in real terms the ways in which the Commission intends to reach EU climate targets under the European Green Deal [[9].

Policy actions and the efforts of industry have led to improvements in fuel efficiency over recent years. For example, the fuel burned per passenger has been reduced a 24% between 2005 and 2017. Nonetheless, the environmental benefits have been outpaced by a sustained growth in air traffic, with passengers in 2017 flying on average 60% further than in 2005.

In the EU in 2017, direct emissions from aviation accounted for 3.8% of total CO_2 emissions. The aviation sector creates 13.9% of the emissions from transport, making it the second biggest source of transport GHG emissions after road transport.

To achieve 2050 zero net goal, the European Green Deal has flagged the necessity to decrease air transport emissions by 90% when comparing to levels of last decade of the previous century.

In 2016, the International Civil Aviation Organization (ICAO) developed a resolution for a global market-based measure to address CO_2 emissions from international aviation as of 2021. The agreed resolution establishes the goals and key design elements of the global scheme, together with a roadmap for the completion of the work on implementing modalities.

The Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA, aims to stabilise CO2 emissions at 2020 levels by requiring airlines to offset the growth of their emissions after 2020. Due to this regulation / agreement, airlines will be required to:

- Monitor emissions on the international routes.
- Offset emissions from routes included in the scheme by purchasing eligible emission units generated by projects that reduce emissions in other sectors (i.e., carbon credits).

During the period 2021-2035, and based on expected participation, the scheme is estimated to offset around 80% of the emissions above 2020 levels. This is because participation in the first phases is voluntary for states, and there are exemptions for those with low aviation activity. All EU countries will join the scheme from the start. Several progresses are being done at ICAO in order to elaborate the required implementation rules and tools to make the scheme operational. Effective and concrete implementation and operationalisation of CORSIA will ultimately depend on national measures to be developed and enforced at domestic level.

4.2 CARBON CREDITS MANAGEMENT

As aforementioned, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a carbon offset and carbon reduction scheme to lower CO_2 emissions for international flights, to curb the aviation impact on climate change, and carbon credit management is a hot topic related with the scheme defined by international government organizations in order to reach the 2050 zero net goal [[11].

A carbon credit is a generic term for any tradable certificate or permit representing the right to emit a set amount of carbon dioxide or the equivalent amount of a different greenhouse gas (tCO_2e).

Carbon credits and carbon markets are a component of national and international attempts to mitigate the growth in concentrations of greenhouse gases (GHGs). One carbon credit is equal to one ton of carbon dioxide, or in some markets, carbon dioxide equivalent gases. Carbon trading is an application of an emissions trading approach. Greenhouse gas emissions are capped and then markets are used to allocate the emissions among the group of regulated sources.

The goal is to allow market mechanisms to drive industrial and commercial processes in the direction of low emissions or less carbon intensive approaches than those used when there is no cost to emitting carbon dioxide and other GHGs into the atmosphere. Since GHG mitigation projects generate credits, this approach can be used to finance carbon reduction schemes between trading partners around the world [[10].

There are also many companies that sell carbon credits to commercial and individual customers who are interested in lowering their carbon footprint on a voluntary basis. These carbon off-setters purchase the credits from an investment fund or a carbon development company that has aggregated the credits from individual projects. Buyers and sellers can also use an exchange platform to trade, which is like a stock exchange for carbon credits. The quality of the credits is based in part on the validation process and sophistication of the fund or development company that acted as the sponsor to the carbon project. This is reflected in their price; voluntary units typically have less value than the units sold through the rigorously validated Clean Development Mechanism. The European Union's carbon credits traded from \$7.78 to \$25.19 averaging \$16.21 per ton in 2018. Although it remains in development, it is anticipated that the value and trading of carbon credits will continue to grow.

5 ECONOMICAL ANALYSIS

In this section, it is presented the economic analysis of the MVP developed. Firstly, a cost analysis is presented, aiming to set the price of the technological implementation required to achieve the AFC actuation desired in the aircraft Airbus A-320. Then, the aerodynamic benefits are estimated based on the results presented in the previous section. The next section presented aims to describe the methodology applied for gathering the required input regarding air traffic data. Next, the hypothesis the economic study is based on are presented, justifying the considerations and assumptions considered in the analysis. Finally, the feasibility study of each of the cases analysed is presented, together with the main results analysis [[26].

5.1 MVP COST ANALYSIS

In this section, the cost analysis of the MVP is presented. It should be noted that, since the technology to be implemented so as to build the proposed MVP is currently under development, the information regarding prices is not easy to find. Therefore, the main components are initially presented, and then the price is set up based on the cost analysis of similar actuators and sensors currently used in aeronautical industry.

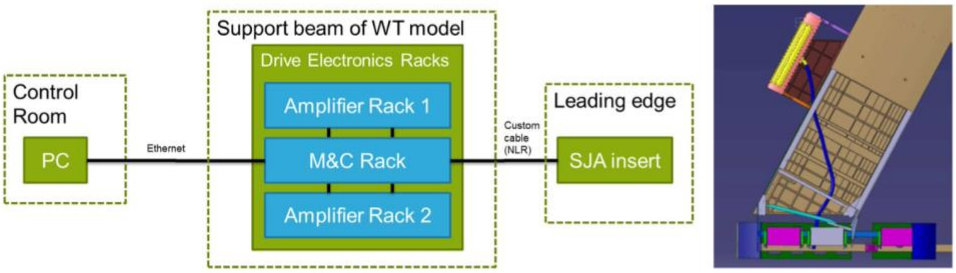


Figure 22. System design for a Synthetic Jet Actuator [15]

An overview of the complete system design for the synthetic jet actuator AFC system is shown in Figure 22. It consists of three different parts [[15]:

- The SJA insert box for the housing of the actuators and the integration in the wing section of the wind tunnel model.
- Signal conditioning, actuator excitation and monitoring equipment, located as close as possible to the wind tunnel model (drive electronics subracks).
- The human–machine interface (HMI) computer for con- trol, data recording and visualization.

The drive electronics system consists of two high voltage (HV) amplifier subracks that are controlled by a measurement control (M&C) subrack. It provides high- voltage excitation signals from 0 up to 200 V for the actuators. It also monitors the status of the system and the status of the individual actuators.

The synthetic jet actuators considered for the analysis are based on piezo-electric transducers. They are equipped with a two-pin electrical connector for the HV input signal and an outlet on the upper side of the housing, and the actuators have a polymeric housing, as can be seen in Figure 23.

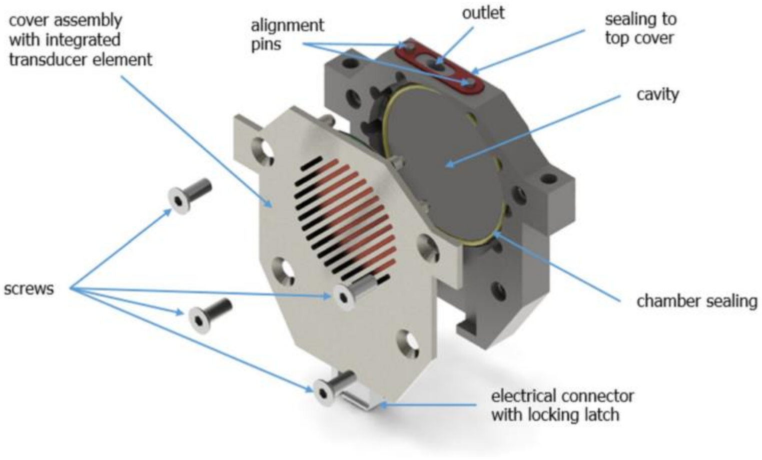


Figure 23. Synthetic jet actuator schematic representation [15]

Considering the main components described above, and based on bibliographic research, the price of the synthetic jet actuator pack, together with the sensors and the power supply distribution and power storage is set to be between **50k€ and 70k€** [[20] for a complete pack (understanding as a pack the ten different actuators that are installed in the airfoil, with the predefined configuration of 2 actuators on the slat, 3 on the fixed part of the wing and 5 on the flap (2,3,5 configuration). A total of 5 packs are needed per wing, meaning that a total of **10 packs are to be installed per aircraft** [[12]. Therefore, the required **investment per aircraft to install the MVP is between 500k€ and 700k€**, without considering the margin that can be additionally included in the whole price per part of the company installing the systems, and neither the possible depreciation that can be applied to the final price when purchasing and installing the systems in a considerably high number of aircrafts.

5.2 AERODYNAMIC BENEFITS OF THE MVP

In this subsection, the main results related with the aerodynamic benefits offered by the proposed MVP obtained in the physical study presented in this thesis are shown, focusing on the Airbus A-320 aircraft model. In Figure 24 and Figure 25 the key results are presented.

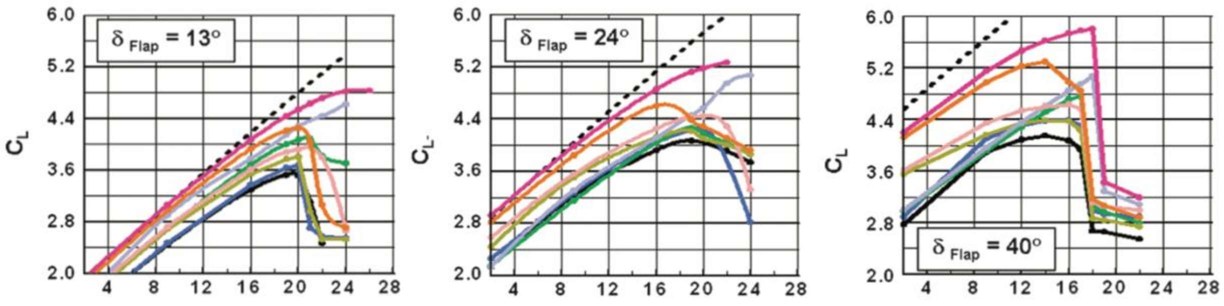


Figure 24. C_L versus angle of attack obtained in the three casuistic studied [12]

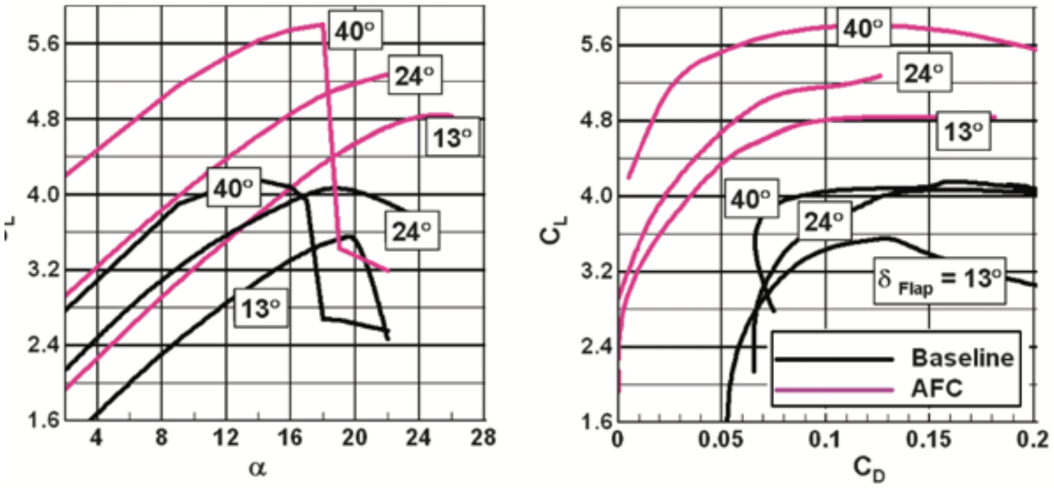


Figure 25. CL versus angle of attack and C_L versus C_D of the three casuistic studied [12]

In the table below, the summary of the lift and drag benefits obtained per each casuistic is presented.

Casuistic analysed	**Lift increasement (average)**	**Drag reduction (average)**
Take-off, delta_flap 13º	17% - 37% (27)	35% - 40% (37.5)
Take-off, delta_flap 24º	15% - 32% (23.5)	40% - 50% (45)
Landing, delta_flap 40º	28% - 45% (36.5)	45% - 55% (50)

Table 1. Main results of the analytical study

As stated in previous section, the key objective of the MVP is to reduce the fuel consumption of the aircraft, and ultimately reduce the carbon footprint of the air traffic industry. Therefore, the aerodynamic improvement achieved by implementing the AFC technology described as the MVP presented throughout this thesis allows to present a higher lift at a lower angle of attack, and thereby reducing considerably the total drag. Based on results previously presented, it is stated that the aerodynamic improvement achieved by implementing the MVP in an Airbus A-320 represents an **average drag reduction of 44% in landing and take-off operations**. It is considered as a hypothesis that the reduction in drag obtained due to the implementation of the AFC technology of this MVP translates into the same percentage of fuel reduction multiplied by an efficiency factor of 70%, to also address the energy consumed by the AFC technological systems. In this way, it is estimated that the **reduction of fuel in landing and take-off operations of 30%**.

5.3 AIR TRAFFIC DATA GATHERING METHODOLOGY

In order to conduct the feasibility study of the project, three different situations are considered:

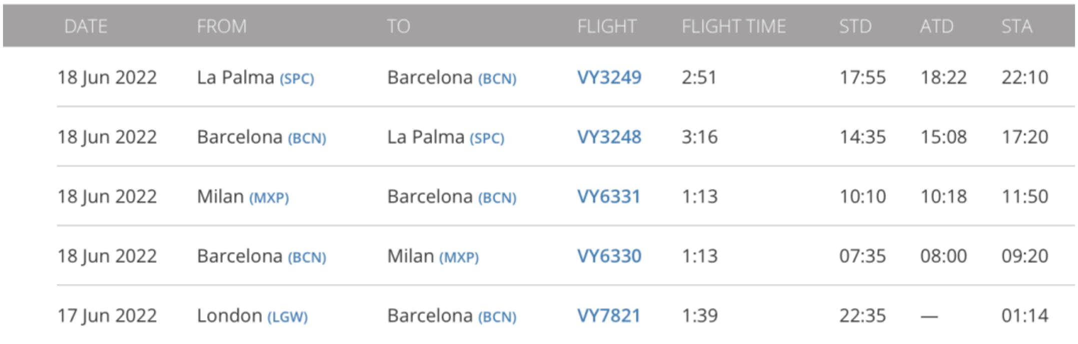
- Economic study of one Airbus A-320 considering only national flights in Spain.
- Economic study of one Airbus A-320 considering international flights in Europe.
- Economic study of a fleet of Airbus A-320 considering international flights in Europe.

Therefore, air traffic data is required so as to estimate the number of flights to be considered in each perspective defined. To do so, a Swedish internet-based service that shows real-time commercial flight information has been used [[19]. This service includes tracking of flights, origins and destinations, flight numbers, aircraft types, positions, altitudes, directions and speeds. It should be noted that, in the service offered for free, it is only possible to access flight data in the last 7 days. Therefore, to analyze longer periods, the data available in the previous 7 days are considered as the basis of the estimate and are calculated proportionally based on the initial period.

The search methodology consists of analyzing three national airlines that also operate at a European level (i.e., Vueling, Iberia and Easy Jet), the number of flights they carry out at a national level has been counted in the first instance, and at a European level afterwards, to obtain the numbers required for each specific study. To increase the accuracy of the estimation, 30 aircrafts are studied in each case analyzed.

On the other hand, the specific fleet of these three airlines is also analyzed, to arrive at the average number of Airbus A-320 that contains a fleet of airlines of the style (necessary for the third case study).

In Figure 26, a sample of the data obtained by means of the previously mentioned software is presented.



DATE	FROM	TO	FLIGHT	FLIGHT TIME	STD	ATD	STA
18 Jun 2022	La Palma (SPC)	Barcelona (BCN)	VY3249	2:51	17:55	18:22	22:10
18 Jun 2022	Barcelona (BCN)	La Palma (SPC)	VY3248	3:16	14:35	15:08	17:20
18 Jun 2022	Milan (MXP)	Barcelona (BCN)	VY6331	1:13	10:10	10:18	11:50
18 Jun 2022	Barcelona (BCN)	Milan (MXP)	VY6330	1:13	07:35	08:00	09:20
17 Jun 2022	London (LGW)	Barcelona (BCN)	VY7821	1:39	22:35	—	01:14

Figure 26. Sample of air traffic data obtained through the internet-based service [19]

5.3.1 Case 1: Airbus A-320 weekly national flights in Spain

In this subsection the results obtained for the air traffic data gathering for only national flights in Spain of an Airbus A-320 are presented, in the table below.

Model	**ID**	**Airline**	**# of flights**
Airbus A-320	EC-JGM	Vueling	9
Airbus A-320	EC-JSY	Vueling	17
Airbus A-320	EC-JTQ	Vueling	27
Airbus A-320	EC-JTR	Vueling	24
Airbus A-320	EC-JYX	Vueling	29
Airbus A-320	EC-JZI	Vueling	39
Airbus A-320	EC-KCU	Vueling	19
Airbus A-320	EC-KDG	Vueling	10
Airbus A-320	EC-KDH	Vueling	20
Airbus A-320	EC-KDT	Vueling	13
Airbus A-320	EC-IEF	Iberia	7
Airbus A-320	EC-IEG	Iberia	13
Airbus A-320	EC-ILS	Iberia	13
Airbus A-320	EC-IZH	Iberia	14
Airbus A-320	EC-IZR	Iberia	8
Airbus A-320	EC-JFN	Iberia	12
Airbus A-320	EC-KOH	Iberia	13
Airbus A-320	EC-LRG	Iberia	12
Airbus A-320	EC-LUL	Iberia	29
Airbus A-320	EC-LVD	Iberia	27
Airbus A-320	G-EZGX	Easy jet	3
Airbus A-320	G-EZGY	Easy jet	4
Airbus A-320	G-EZOA	Easy jet	2
Airbus A-320	G-EZOF	Easy jet	5
Airbus A-320	G-EZOI	Easy jet	2
Airbus A-320	G-EZOK	Easy jet	1
Airbus A-320	G-EZOM	Easy jet	4
Airbus A-320	G-EZRZ	Easy jet	0
Airbus A-320	G-EZRY	Easy jet	1
Airbus A-320	G-EZTB	Easy jet	3

Table 2. Air traffic data for weekly national flights (Spain)

Based on the previous results, the average of national flights carried out by an Airbus A-320 aircraft belonging to the fleet of a typical low-cost airline can be set to **13 flights per week in Spain**.

On the other hand, based on the data gathered it can be stated that the **average price per ticket** for Airbus A-320 flights in Spain to be considered is **100€**, and regarding **average distance**, it can be set to **650 kilometres per flight** [[19].

5.3.2 Case 2: Airbus A-320 weekly international flights in Europe

In this subsection the results obtained for the air traffic data gathering for only national flights in Spain of an Airbus A-320 are presented, in the table below.

Model	**ID**	**Airline**	**# of flights**
Airbus A-320	EC-JGM	Vueling	21
Airbus A-320	EC-JSY	Vueling	27
Airbus A-320	EC-JTQ	Vueling	22
Airbus A-320	EC-JTR	Vueling	21
Airbus A-320	EC-JYX	Vueling	37
Airbus A-320	EC-JZI	Vueling	12
Airbus A-320	EC-KCU	Vueling	28
Airbus A-320	EC-KDG	Vueling	32
Airbus A-320	EC-KDH	Vueling	14
Airbus A-320	EC-KDT	Vueling	18
Airbus A-320	EC-IEF	Iberia	30
Airbus A-320	EC-IEG	Iberia	17
Airbus A-320	EC-ILS	Iberia	31
Airbus A-320	EC-IZH	Iberia	25
Airbus A-320	EC-IZR	Iberia	16
Airbus A-320	EC-JFN	Iberia	15
Airbus A-320	EC-KOH	Iberia	32
Airbus A-320	EC-LRG	Iberia	23
Airbus A-320	EC-LUL	Iberia	25
Airbus A-320	EC-LVD	Iberia	28
Airbus A-320	G-EZGX	Easy jet	36

Airbus A-320	G-EZGY	Easy jet	23
Airbus A-320	G-EZOA	Easy jet	36
Airbus A-320	G-EZOF	Easy jet	43
Airbus A-320	G-EZOI	Easy jet	25
Airbus A-320	G-EZOK	Easy jet	42
Airbus A-320	G-EZOM	Easy jet	38
Airbus A-320	G-EZRZ	Easy jet	27
Airbus A-320	G-EZRY	Easy jet	19
Airbus A-320	G-EZTB	Easy jet	41

Table 3. Air traffic data for weekly international flights (Europe)

Based on the previous results, the average of international flights carried out by an Airbus A-320 aircraft belonging to the fleet of a typical low-cost airline can be set to **27 flights per week in Europe**.

On the other hand, based on the data gathered it can be stated that the **average price per ticket** for Airbus A-320 flights in Spain to be considered is **150€**, and regarding **average distance**, it can be set to **850 kilometres per flight** [[19].

5.3.3 Case 3: Number of Airbus A-320 in a low-cost airline fleet

In the third case of study, as aforementioned, the objective is to obtain the average number of Airbus A-320 aircraft in a typical low-cost airline structure analysed. The number of Airbus A-320 in each of the airlines studied in this section is presented in the table below.

Airline	**# of Airbus A-320**
Vueling	76
Iberia	13
Easy jet	173

Table 4. Number of Airbus A-320 in low-cost airline fleet

Based on the results, it is possible to define as the **average number of Airbus A-320 aircraft in a typical low-cost airline as 85**.

5.4 HYPOTHESIS CONSIDERED

In this subsection, the main hypothesis considered when conducting the feasibility study of the project are presented:

- The economic study is carried out from the perspective of an airline that aims to install the MVP in its aircraft to increase the aerodynamic efficiency of its fleet, as well as to reduce the carbon footprint of its operational activity.
- The elements to be installed have been selected in such a way that they are compatible with the electrical and electronic installation of the Airbus A-320, so it is possible to include the technology in currently working aircraft as an extra addition [[15].
- To calculate the costs, the costs associated with the installation equipment are not considered; it is based on the hypothesis that the company from the perspective of which the economic study is proposed has already the necessary machinery to install it.
- As a consequence of the previous point, a profit margin of a 30% for the installation company will be added to the calculation of the economic study.
- The average price of kerosene to be considered, based on the researched data, is to be 2.17€ per gallon (that is, every 3.8 liters), equivalent to 0.57€ per liter [[18].
- As previously mentioned, the designed AFC device is used in the take-off, climb, descent and landing phases of the flight. The flight duration of these phases can be estimated to be between 20% and 40% of the flight, for the type of flights considered in the studies here presented. Therefore, it is considered that the technology is used in 30% of the flight, providing previously defined fuel savings [[19].
- A kilogram of aeronautical jet fuel (kerosene) consumed emits a total of 3.16 kilograms of CO_2 to the atmosphere, or what is the same, a total of 2.6 kilograms of CO_2 per liter of kerosene burned [[17].
- Approximately it is estimated that the value of avoiding the emission of a ton of CO_2 to the atmosphere is 10€ [[23].
- An average consumption of the Airbus A-320 model is considered to be a total of 771 gallons per hour, which is equivalent to about 2918 liters per hour. As far as speed is concerned, an average cruising speed of 828 kilometers per hour is established, which allows to define an average fuel consumption of 352.7 liters per 100 km [[17].
- Due to the great global awareness that exists regarding climate change, and as a consequence the generalized intention of large industries to reduce their carbon footprint, it is considered as a hypothesis that airport fees reduce by 5% for airlines that implement this technology [[12].
- Due to the installation of AFC technology, the annual maintenance cost will be considered 5% more expensive than usual. On average, an Airbus A-320 aircraft is considered to have a maintenance cost of 700€ per flight hour [[17].
- The maximum passenger load capacity of the Airbus A-320 aircraft model is 180. It is estimated that the average number of passengers on each flight is 140 passengers [[17].

- On average, the airport fees, considering both landing and government fees, for the Airbus A-320 aircraft model at the main Spanish airports is 500€, while at the main European airports it is 700€ [[17].
- Due to the current social awareness, it is considered that the fact of incorporating the AFC technology presented in the MVP with the aim of reducing the carbon footprint represents an increase in ticket sales for passengers of 0.5%. On the other hand, it should be noted that in the coming years the existing regulations regarding emission of polluting gases in the aeronautical industry will be more demanding, even proposing a tax per passenger in those aircraft that do not respect certain limits.

5.5 FEASIBILITY STUDY

This section presents the feasibility analysis of the MVP, from the different perspectives mentioned above. Firstly, a preliminary analysis is carried out in the three case studies, in such a way that it is possible to determine if the project is profitable a priori. It should be noted that for each casuistry two differentiated studies are conducted: the first study in which only the differential factors that will occur with high certainty are considered (i.e., fuel savings, increase in the maintenance costs and the initial investment), while in the second study, the previously described hypotheses are considered (i.e., increase in ticket sales, air traffic growth, airport fees reduction and value of carbon credits) [[24] [[26] [[27].

5.5.1 Preliminary study without considering hypotheses

In this subsection, the results of the preliminary study are detailed, considering only the differential factors that will occur with total certainty (i.e., fuel savings, increase in the maintenance budget and the initial investment).

5.5.1.1 Preliminary study for an aircraft with flights at Spanish level

The tables obtained for the preliminary study are presented below in the case of a single aircraft that makes national flights to Spain.

As can be seen in the results below, the payback time of the inversion is greater than 10 years, making the investment not feasible already at this preliminary stage of the study.

MVP not installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
13	676	439.400	1.549.764	883.365 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment**	**Ticket sales**
70.000 €	N/A	N/A	N/A	9.464.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
338.000 €	455.000 €

Table 5. Preliminary study 1: Costs with MVP not installed

MVP installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
13	676	439.400	1.363.792	777.362 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**
70.000 €	5	10	910.000 €	9.464.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
338.000 €	477.750 €

Table 6. Preliminary study 1: Costs with MVP installed

Difference					
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**	**CO2 kilograms not emitted**
N/A	N/A	N/A	185.972	106.004 €	483.526

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**	**Value of CO2 tones avoided**
70.000 €	5	10	910.000 €	- €	4.835 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
- €	22.750 €

Global result [€]
83.254 €

Table 7. Preliminary study 1: Difference between the two cases

5.5.1.2 Preliminary study for an aircraft at European level

Subsequently, the results are presented for the case of a single aircraft that performs flights at European level.

MVP not installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
27	1404	1.193.400	4.209.122	2.399.199 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment**	**Ticket sales**
70.000 €	N/A	N/A	N/A	29.484.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
982.800 €	455.000 €

Table 8. Preliminary study 2: Costs with MVP not installed

MVP installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
27	1404	1.193.400	3.704.027	2.111.295 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**
70.000 €	5	10	910.000 €	29.484.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
982.800 €	477.750 €

Table 9. Preliminary study 2: Costs with MVP installed

Difference					
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**	**CO2 kilograms not emitted**
N/A	N/A	N/A	505.095	287.904 €	1.313.246

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**	**Value of CO2 tones avoided**
70.000 €	5	10	910.000 €	- €	13.132 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
- €	22.750 €

Global result [€]
265.154 €

Table 10. Preliminary study 2: Difference between the two cases

In this case, it can be seen that the payback of the investment is slightly greater than 3 years, which makes the investment very attractive.

5.5.1.3 Preliminary study for a fleet at European level

The results for a complete fleet of 85 Airbus A-320 aircraft in the case of international European flights are presented below.

MVP not installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
2295	119340	101.439.000	357.775.353	203.931.951 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment**	**Ticket sales**
70.000 €	N/A	N/A	N/A	2.506.140.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
83.538.000 €	38.675.000 €

Table 11. Preliminary study 3: Costs with MVP not installed

MVP installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
2295	119340	101.439.000	314.842.311	179.460.117 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**
70.000 €	5	10	77.350.000 €	2.506.140.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
83.538.000 €	40.608.750 €

Table 12. Preliminary study 3: Costs with MVP installed

Difference					
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**	**CO2 kilograms not emitted**
N/A	N/A	N/A	42.933.042	24.471.834 €	111.625.910

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**	**Value of CO2 tones avoided**
70.000 €	5	10	77.350.000 €	- €	1.116.259 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
- €	1.933.750 €

Global result [€]
22.538.084 €

Table 13. Preliminary study 3: Difference between the two cases

Again, in this casuistry the payback time is slightly over 3 years, which makes the investment very attractive.

5.5.2 Preliminary study considering hypotheses

This subsection details the results of the preliminary study considering the hypotheses described (i.e., increase in ticket sales, growth in air traffic, reduction in airport fees and value of carbon credits).

5.5.2.1 Preliminary study for an aircraft with flights at Spanish level

Firstly, the case of a single plane that makes flights at a national level in Spain.

MVP not installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
13	676	439.400	1.549.764	883.365 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment**	**Ticket sales**
70.000 €	N/A	N/A	N/A	9.464.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
338.000 €	455.000 €

Table 14. Preliminary study 4: Costs with MVP not installed

MVP installed				
Weekly flights average	Yearly flights average	Yearly distance average [km]	Yearly fuel consumption [l]	Yearly fuel consumption cost [€]
13	676	439.400	1.363.792	777.362 €

Cost per AFC pack [€]	# of packs per wing	# of packs per aircraft	Initial investment (30% margin)	Ticket sales
70.000 €	5	10	910.000 €	9.511.320 €

Yearly airport fee costs [€]	Yearly maintenance cost [€]
321.100 €	477.750 €

Table 15. Preliminary study 4: Costs with MVP installed

Difference					
Weekly flights average	Yearly flights average	Yearly distance average [km]	Yearly fuel consumption [l]	Yearly fuel consumption cost [€]	CO2 kilograms not emitted
N/A	N/A	N/A	185.972	106.004 €	483.526

Cost per AFC pack [€]	# of packs per wing	# of packs per aircraft	Initial investment (30% margin)	Ticket sales	Value of CO2 tones avoided
70.000 €	5	10	910.000 €	47.320 €	4.835 €

Yearly airport fee costs [€]	Yearly maintenance cost [€]
16.900 €	22.750 €

Global result [€]
147.474 €

Table 16. Preliminary study 4: Difference between the two cases

As can be seen, when considering the hypotheses, the payback time of the investment is reduced by a considerable percentage; however, it is still longer than 6 years, so after analysing the preliminary study it is possible to conclude that this option is not viable, without the need for more detailed studies.

5.5.2.2 Preliminary study for an aircraft with flights at European level

Subsequently, the results obtained for the case of a single aircraft that performs international flights at European level are presented.

MVP not installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
27	1404	1.193.400	4.209.122	2.399.199 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment**	**Ticket sales**
70.000 €	N/A	N/A	N/A	29.484.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
982.800 €	455.000 €

Table 17. Preliminary study 5: Costs with MVP not installed

MVP installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
27	1404	1.193.400	3.704.027	2.111.295 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**
70.000 €	5	10	910.000 €	29.631.420 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
933.660 €	477.750 €

Table 18. Preliminary study 5: Costs with MVP installed

Difference					
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**	**CO2 kilograms not emitted**
N/A	N/A	N/A	505.095	287.904 €	1.313.246

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**	**Value of CO2 tones avoided**
70.000 €	5	10	910.000 €	147.420 €	13.132 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
49.140 €	22.750 €

Global result [€]
461.714 €

Table 19. Preliminary study 5: Difference between the two cases

Once again, when considering the established hypotheses, the result improves considerably, managing to reduce the payback time to just under 2 years.

5.5.2.3 Preliminary study for a fleet at European level

Finally, the preliminary results are presented for the case of a fleet of 85 aircraft in the case of international flights at European level.

MVP not installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
2295	119340	101.439.000	357.775.353	203.931.951 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment**	**Ticket sales**
70.000 €	N/A	N/A	N/A	2.506.140.000 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
83.538.000 €	38.675.000 €

Table 20. Preliminary study 6: Costs with MVP not installed

MVP installed				
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**
2295	119340	101.439.000	314.842.311	179.460.117 €

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**
70.000 €	5	10	77.350.000 €	2.518.670.700 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
79.361.100 €	40.608.750 €

Table 21. Preliminary study 6: Costs with MVP installed

Difference					
Weekly flights average	**Yearly flights average**	**Yearly distance average [km]**	**Yearly fuel consumption [l]**	**Yearly fuel consumption cost [€]**	**CO2 kilograms not emitted**
N/A	N/A	N/A	42.933.042	24.471.834 €	111.625.910

Cost per AFC pack [€]	**# of packs per wing**	**# of packs per aircraft**	**Initial investment (30% margin)**	**Ticket sales**	**Value of CO2 tones avoided**
70.000 €	5	10	77.350.000 €	12.530.700 €	1.116.259 €

Yearly airport fee costs [€]	**Yearly maintenance cost [€]**
4.176.900 €	1.933.750 €

Global result [€]
39.245.684 €

Table 22. Preliminary study 6: Difference between the two cases

5.5.3 Preliminary studies analysis

As briefly mentioned in each of the cases studied, the preliminary results allow the casuistry raised to be filtered in such a way that the feasibility study is focused on the case of greatest interest in terms of numbers. Therefore, it is possible to conclude that the case of most interest is the third analysed, that is the one for the fleet of 85 Airbus A-320 aircraft, for which the feasibility study is developed in the next section at 5 years' time considering the previously mentioned hypotheses.

5.5.4 Complete feasibility analysis: MVP installed in a fleet of 85 Airbus A-320

As previously introduced, in this section a complete feasibility analysis is conducted for the case in which the MVP is installed in a fleet of 85 Airbus A-320 aircraft, in order to state whether the project would be attractive from an economic point of view.

To do so, three cases are analysed with situations that are described in each respective subsection:

- Optimistic scenario, in which the majority of the favourable factors that influence the overall pricing of the project evolve positively.
- Pessimistic scenario, in which the majority of the negative factors that influence the overall pricing of the project evolve negatively.
- Most likely scenario, in which both positive and negative factors that influence the overall pricing of the project e volve following the last years trends.

The main factors considered when conducting the exercise are listed below:

1. Initial investment.
2. Fuel consumption (in terms of fuel price).
3. Maintenance costs.
4. Airport fees.
5. Ticket sales.
6. Carbon credit taxes.

5.5.4.1 Feasibility study: optimistic scenario

In this subsection, the optimistic scenario is presented. Since the objective in this particular case is to showcase a possible scenario in which the factors positively impacting the project evolve favourably, the following considerations are taken:

a. Due to the large number of AFC packs to be installed (a total of 850), the manufacturing company reduces the price of each from 70.000€ to 55.000€ (cost reduction due to economy of scale).

b. The fuel price is considered to have a yearly increase of a 5%.

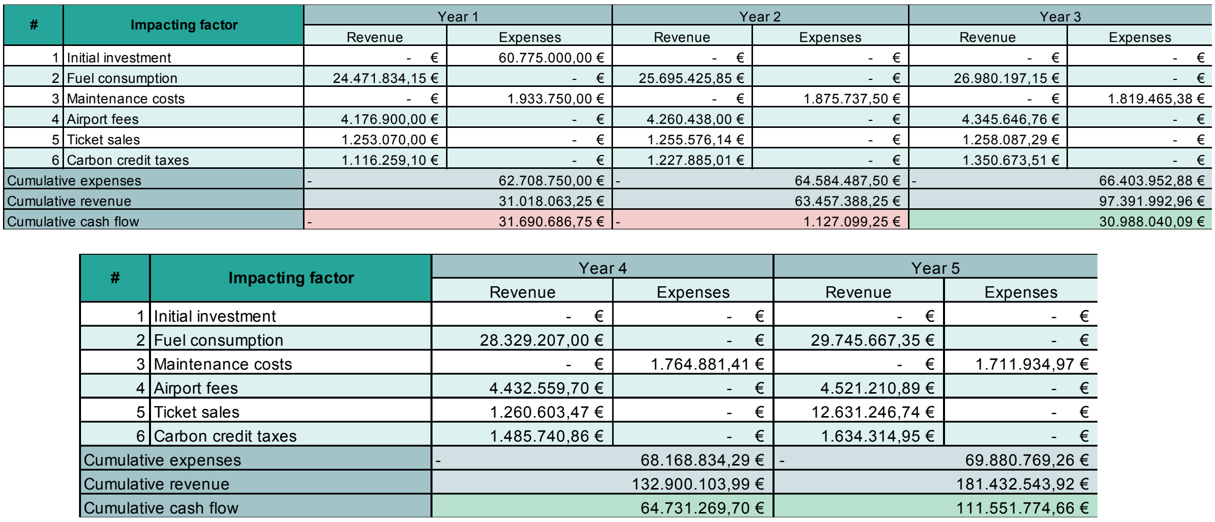
c. Maintenance costs evolution is considered to reduce a 3% yearly, since the operators are more familiarized with the systems.

d. Airport fees are increased an additional 2% yearly, since the airport costs are increasing accordingly.

e. A new regulation arises in which the aircraft that do not install any system to reduce carbon footprint must pay an additional fee, and the passengers would need to pay extra money per flight. Therefore, the ticket sales are considered to increase a 0.2% yearly.

f. Carbon credit taxes are increasing, so the price per ton of CO_2 avoided is increasing a 10% yearly.

In the table below, the results obtained for the feasibility study of the optimistic scenario are presented.



#	Impacting factor	Year 1		Year 2		Year 3	
		Revenue	Expenses	Revenue	Expenses	Revenue	Expenses
1	Initial investment	- €	60.775.000,00 €	- €	- €	- €	- €
2	Fuel consumption	24.471.834,15 €	- €	25.695.425,85 €	- €	26.980.197,15 €	- €
3	Maintenance costs	- €	1.933.750,00 €	- €	1.875.737,50 €	- €	1.819.465,38 €
4	Airport fees	4.176.900,00 €	- €	4.260.438,00 €	- €	4.345.646,76 €	- €
5	Ticket sales	1.253.070,00 €	- €	1.255.576,14 €	- €	1.258.087,29 €	- €
6	Carbon credit taxes	1.116.259,10 €	- €	1.227.885,01 €	- €	1.350.673,51 €	- €
Cumulative expenses		- 62.708.750,00 €		- 64.584.487,50 €		- 66.403.952,88 €	
Cumulative revenue		31.018.063,25 €		63.457.388,25 €		97.391.992,96 €	
Cumulative cash flow		- 31.690.686,75 €		- 1.127.099,25 €		30.988.040,09 €	

#	Impacting factor	Year 4		Year 5	
		Revenue	Expenses	Revenue	Expenses
1	Initial investment	- €	- €	- €	- €
2	Fuel consumption	28.329.207,00 €	- €	29.745.667,35 €	- €
3	Maintenance costs	- €	1.764.881,41 €	- €	1.711.934,97 €
4	Airport fees	4.432.559,70 €	- €	4.521.210,89 €	- €
5	Ticket sales	1.260.603,47 €	- €	12.631.246,74 €	- €
6	Carbon credit taxes	1.485.740,86 €	- €	1.634.314,95 €	- €
Cumulative expenses		- 68.168.834,29 €		- 69.880.769,26 €	
Cumulative revenue		132.900.103,99 €		181.432.543,92 €	
Cumulative cash flow		64.731.269,70 €		111.551.774,66 €	

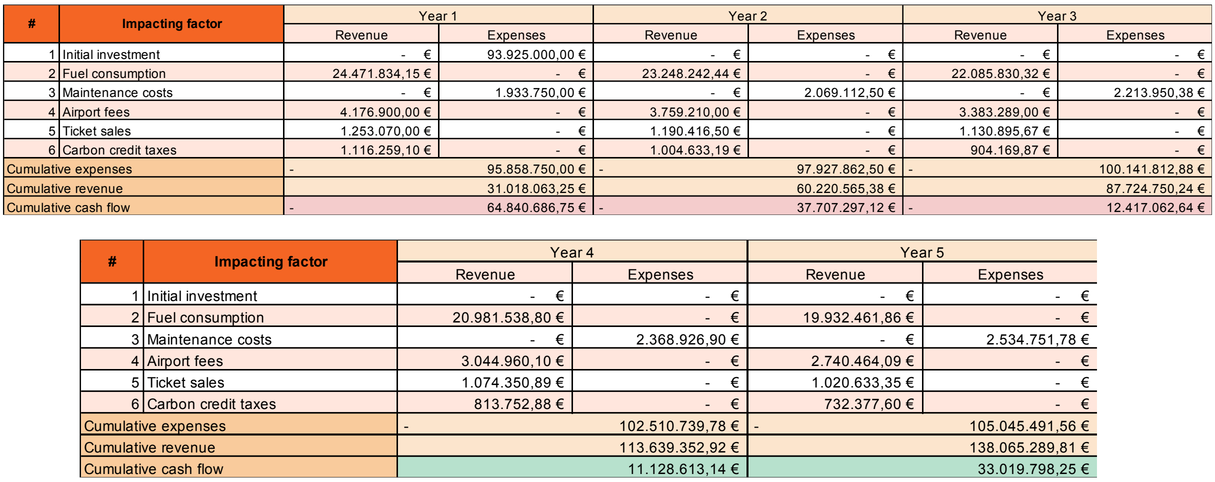
Table 23. Optimistic scenario: feasibility study results

5.5.4.2 Feasibility study: pessimistic scenario

In this subsection, the pessimistic scenario is presented. Since the objective in this particular case is to showcase a possible scenario in which the factors impacting the project evolve negatively, the following considerations are taken:

a. Due to the materials required so as to install each AFC pack, the manufacturing company increases the price of each from 70.000€ to 85.000€.
b. The fuel price is considered to have a yearly decrease of a 5%.
c. Maintenance costs evolution is considered to increase a 7% yearly, since the operators need additional training to be able to conduct maintenance activities to this type of systems.
d. Airport fees are decreased an additional 10% yearly since the strategy defined by the governance organizations is aggressive.
e. The air traffic demand is decreasing due to high costs, and therefore the ticket sales are considered to reduce a 5% yearly.
f. Carbon credit taxes are not being as used as theoretically, so the price per ton of CO_2 avoided is decreasing a 10% yearly.

In the table below, the results obtained for the feasibility study of the pessimistic scenario are presented.



#	Impacting factor	Year 1		Year 2		Year 3	
		Revenue	Expenses	Revenue	Expenses	Revenue	Expenses
1	Initial investment	- €	93.925.000,00 €	- €	- €	- €	- €
2	Fuel consumption	24.471.834,15 €	- €	23.248.242,44 €	- €	22.085.830,32 €	- €
3	Maintenance costs	- €	1.933.750,00 €	- €	2.069.112,50 €	- €	2.213.950,38 €
4	Airport fees	4.176.900,00 €	- €	3.759.210,00 €	- €	3.383.289,00 €	- €
5	Ticket sales	1.253.070,00 €	- €	1.190.416,50 €	- €	1.130.895,67 €	- €
6	Carbon credit taxes	1.116.259,10 €	- €	1.004.633,19 €	- €	904.169,87 €	- €
Cumulative expenses		- 95.858.750,00 €		- 97.927.862,50 €		- 100.141.812,88 €	
Cumulative revenue		31.018.063,25 €		60.220.565,38 €		87.724.750,24 €	
Cumulative cash flow		- 64.840.686,75 €		- 37.707.297,12 €		- 12.417.062,64 €	

#	Impacting factor	Year 4		Year 5	
		Revenue	Expenses	Revenue	Expenses
1	Initial investment	- €	- €	- €	- €
2	Fuel consumption	20.981.538,80 €	- €	19.932.461,86 €	- €
3	Maintenance costs	- €	2.368.926,90 €	- €	2.534.751,78 €
4	Airport fees	3.044.960,10 €	- €	2.740.464,09 €	- €
5	Ticket sales	1.074.350,89 €	- €	1.020.633,35 €	- €
6	Carbon credit taxes	813.752,88 €	- €	732.377,60 €	- €
Cumulative expenses		- 102.510.739,78 €		- 105.045.491,56 €	
Cumulative revenue		113.639.352,92 €		138.065.289,81 €	
Cumulative cash flow		11.128.613,14 €		33.019.798,25 €	

Table 24. Pessimistic scenario: feasibility study results

5.5.4.3 Feasibility study: most likely scenario

In this subsection, the most likely scenario is presented. Since the objective in this particular case is to showcase a possible scenario in which the factors impacting the project evolve following real trends, the following considerations are taken:

a. Due to the large number of AFC packs to be installed (a total of 850), the manufacturing company reduces the price of each from 70.000€ to 63.000€ (cost reduction due to economy of scale).

b. The fuel price is considered to have a yearly increase of a 5%.

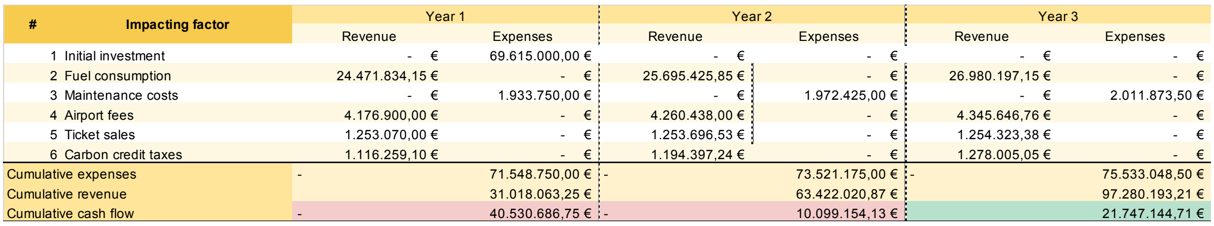
c. Maintenance costs evolution is considered to increase a 2% yearly, since the operators need additional training to be able to conduct maintenance activities to this type of systems.

d. Airport fees are reduced an additional 2% yearly, since the strategy defined by the governance organizations is aggressive.

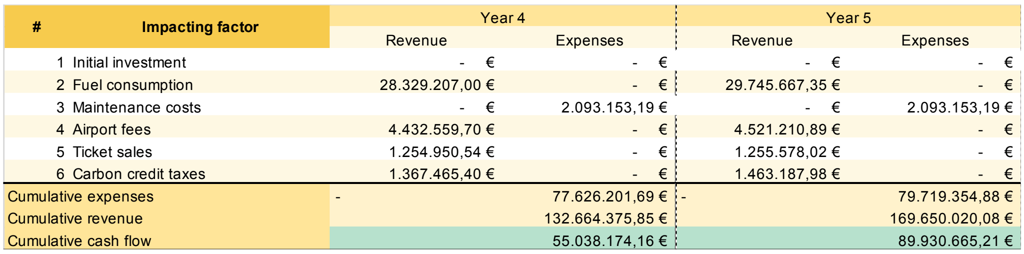
e. The air traffic demand is increasing together with the pre-pandemic recovery, and therefore the ticket sales are considered to increase a 0.05% yearly.

f. Carbon credit taxes are increasing, so the price per ton of CO_2 avoided is increasing a 7% yearly.

In the table below, the results obtained for the feasibility study of the pessimistic scenario are presented.



#	Impacting factor	Year 1		Year 2		Year 3	
		Revenue	Expenses	Revenue	Expenses	Revenue	Expenses
1	Initial investment	- €	69.615.000,00 €	- €	- €	- €	- €
2	Fuel consumption	24.471.834,15 €	- €	25.695.425,85 €	- €	26.980.197,15 €	- €
3	Maintenance costs	- €	1.933.750,00 €	- €	1.972.425,00 €	- €	2.011.873,50 €
4	Airport fees	4.176.900,00 €	- €	4.260.438,00 €	- €	4.345.646,76 €	- €
5	Ticket sales	1.253.070,00 €	- €	1.253.696,53 €	- €	1.254.323,38 €	- €
6	Carbon credit taxes	1.116.259,10 €	- €	1.194.397,24 €	- €	1.278.005,05 €	- €
Cumulative expenses		- 71.548.750,00 €		- 73.521.175,00 €		- 75.533.048,50 €	
Cumulative revenue		31.018.063,25 €		63.422.020,87 €		97.280.193,21 €	
Cumulative cash flow		- 40.530.686,75 €		- 10.099.154,13 €		21.747.144,71 €	



#	Impacting factor	Year 4		Year 5	
		Revenue	Expenses	Revenue	Expenses
1	Initial investment	- €	- €	- €	- €
2	Fuel consumption	28.329.207,00 €	- €	29.745.667,35 €	- €
3	Maintenance costs	- €	2.093.153,19 €	- €	2.093.153,19 €
4	Airport fees	4.432.559,70 €	- €	4.521.210,89 €	- €
5	Ticket sales	1.254.950,54 €	- €	1.255.578,02 €	- €
6	Carbon credit taxes	1.367.465,40 €	- €	1.463.187,98 €	- €
Cumulative expenses		-	77.626.201,69 €	-	79.719.354,88 €
Cumulative revenue			132.664.375,85 €		169.650.020,08 €
Cumulative cash flow			55.038.174,16 €		89.930.665,21 €

Table 25. Most likely scenario: feasibility study results

5.5.4.4 Analysis of the results

After conducting the feasibility analysis, it is possible to conclude that the investment is feasible and attractive from the economic point of view. In all cases, even in the pessimistic scenario, the investment recovers during the first 5 years (between 2 and 4 years, depending on the scenario). Bearing in mind that the useful life of an Airbus A-320 aircraft is between 25 and 30 years, and that the investment per aircraft represents approximately 3% of the total purchase cost of an aircraft with these characteristics, it is considered to be a solid investment capable of providing economic benefits to the company, and on the other hand improve the relationship with the environment [[27].

In Figure 27 both the net and cumulative cash flow obtained for the three scenarios is presented [[25].

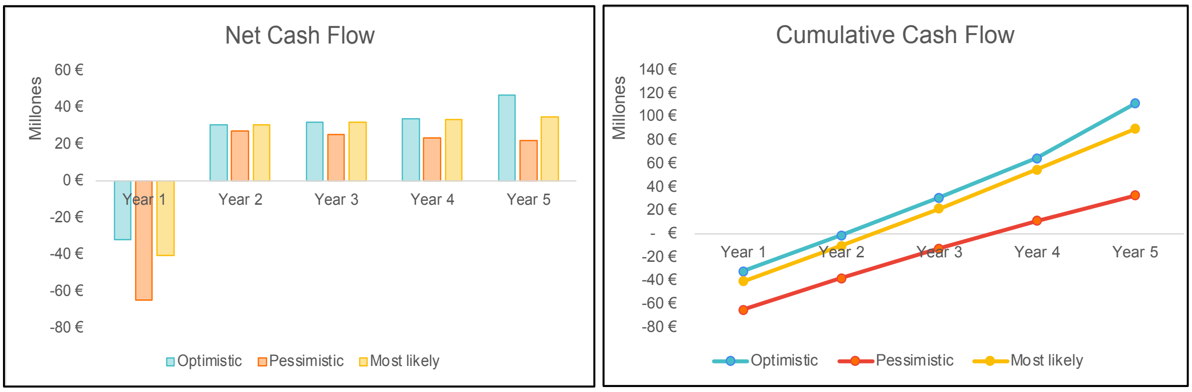


Figure 27. Net (1) and Cumulative (2) investment cash flow evolution

In all cases, due to the initial investment required for the installation of the AFC packs in the aircraft, the cash flow is negative during the first year. However, in the second year the investment starts to be recovered in all three scenarios, and in the cumulative cash flow graph, on the right-hand side, when the lines are crossing the horizontal mark that represents zero, the investment has been fully recovered (payback time).

As a conclusion, it is possible to extract that both graphs above reinforce the arguments about the present MVP; that is, the investment has been proven to be feasible and profitable from an economic perspective.

6 CONCLUSIONS, IMPROVEMENTS AND RECOMMENDATIONS

6.1 CONCLUSIONS

After carrying out such a challenge as it is to define and develop an MVP for a new technology, there are different points that should be commented:

- A complete state-of-the-art of the new technology has been presented, in which the origin of Active Flow Control technology has been described in detail, what are the main fields of application in the market to later deep dive in its main applications in the aeronautical industry, and an MVP has been defined analysing the economic viability of the product with a specific case study for an Airbus A-320 fleet of aircraft.
- What is more, the scope of the project that was initially set has actually been totally reached and, throughout the development of the project, opportunities arose to develop studies related to the project that were not reflected in the scope, and they have been carried out, adding greater value to the thesis.
- Such an ambitious project has encouraged to the author to its development because of the opportunity to perform a multidisciplinary project, in which fields such as research, technological elements implementation, aerodynamics, sustainability and economic planning skills are involved.
- During the thesis' development there has been several times in which the functional background of the author was not enough for studying and solving concrete economic aspects, due to the complexity of the tasks and the lack of pricing information in the market due to the low practical maturity of the studied technology. Therefore, it has been necessary to learn new concepts and quickly adapt to challenging situations.
- Communication with the director and co-director of the thesis has been constant and fluid, maintaining a dynamic of monthly meetings to report progress and to flag outstanding doubts. This methodology has helped to the correct development of the project. As happens in a real project, the communication between all the members who are collaborating is key, and throughout the development of this thesis, this skill has been reinforced.
- This project, which means the end of the master, has finally given to the student quite valuable experience in project managing, planning, defining the key topics, designing and scheduling, being able to define an MVP and analyse its costs, revenues, profitability and viability, but also in estimating coherent hypotheses, estimating time, resources and main objectives to successfully develop and implement the product.
- The particular case for which the MVP has been proposed is very ambitious, due to the fact that it implements high-power actuator systems capable of reducing aerodynamic drag by up to 55% in the take-off and landing phases. It must be considered that the percentage has been obtained through theoretical studies, and is only provided in the previously mentioned phases, so that when studying the viability of the project, a reduction of approximately 10% of the aerodynamic drag in the totality of the flights under study. On the other hand, the case for which the complete economic study has been proposed is the most ambitious of those

studied, but if sufficient advances are made in the technology of the actuators, as well as in the implementation techniques, the long-term benefits would be very relevant.

- As for the results obtained through the economic analysis, conducted for the case in which the MVP is installed in a fleet of 85 Airbus A-320, it should be noted that the required initial investment is huge (i.e., > 70 M€ in the most-likely scenario), and this is a handicap to be considered. However, in terms of the feasibility of the MVP implementation, it has been proven that the investment is recovered after the second year in the most likely and optimistic scenarios, while in the pessimistic scenario it is recovered during the fourth year. Therefore, it is concluded that the implementation of the MVP is a good investment when it comes to economic numbers (providing near to 90 M€ of positive cash flow after the fifth year), and on the other hand it allows to avoid the emission of more than 100 tones of CO_2 yearly.

6.2 IMPROVEMENTS AND RECOMMENDATIONS

Overall, the MVP development accomplishes all the initial requirements set up, and ensures the validity of the results obtained by presenting different casuistic studied, with coherent hypotheses, and on all of them the results are very positive. Nevertheless, there are some recommendations for further improvements.

As previously mentioned, a huge number of studies were related to the technology described in this thesis, and more than 70% are focused on AFC fundamentals. Nevertheless, technological developments or numerical tools for modelling are still from an academic point of view and quite far from what aircraft manufacturing really needs. Currently, there is still a lot of research needed when it comes to bring to the reality the models studied throughout computational analysis due to lack of properly tested technologies in industrially environments to get closer to the real application configurations.

When installing an AFC technological application in an aircraft, it is crucial to consider that the energy to be supplied to the systems have an important impact on the AFC architecture, mass and the choice of its components. The more efficiency required by the AFC system, the more the mass of this system is relevant (1kg/kW for all electric AFC based on SJA). Therefore, the integration of the systems within the aircraft system landscape must be considered when installing the elements, and the total power consumption as well as the safety requirements are key topics when defining an AFC technological architecture in the aeronautical industry.

On the other hand, when installing any type of element in an aircraft, it is well known that the certification process must be exhaustive, in order to ensure compliance with current regulations and to mitigate as much as possible the arisen risks. According to research, only few AFC products have dealt with flow control systems integration and certification, and inflight performances. As any new technology, the AFC systems have to make proof in many fields, such as cost effectiveness, noise generated and reliability, to be fully applicable on civil aircraft.

Below, some topics of interest that may be used as next studies in the field of ACF technology implementation:

- Experimental or computational investigation around turbulent boundary layer separation control due lo large adverse pressure gradients or shock/boundary layer interactions.
- Development of efficient, reliable and energy-efficient actuators for controlling boundary layer separation.
- Exhaustive pricing analysis of technological elements to be installed in an AFC aeronautical project.
- Fabrication and testing of an AFC pack, focusing on the costs to purchase and manufacture a functional system configuration and measuring the aerodynamic effects it may deliver.
- Development of computational tools to model the performance of a proposed actuator technological configuration.
- Development of closed-loop active flow control systems with demonstrated improvements in AFC efficiency measured by the energy consumed by the AFC actuator.
- Experimental evaluation of realistic AFC actuators applied to separated flows.
- Experimental and computational studies that demonstrate the efficiency of the proposed actuation system.
- Development of computational tools to model the flow field resulting from the application of active flow control on an airfoil or wing.

Despite these improvements and recommendations, as already commented, the main objective of this study has been achieved successfully, developing such a valuable MVP and excel templated which can be used for obtaining the main economic results of cost, profitability and feasibility analysis for new projects, giving the student the opportunity to demonstrate all his skills in project management, including planning, scheduling and main objectives determination.

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