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Study of the AFC technology development:

a case study applied to wind turbines

REPORT

Final Master Thesis
in Aerospace Engineering

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Glossary

Symbol	**Definition**
W	Watt
ω	Angular Velocity
m	Meters
v	Velocity
c_L	Lift coefficient
c_M	Moment coefficient
v	Velocity
$\dot{m}$	Mass flow rate
ρ	Density
C_μ	Energy consumption
α	Angle of Attack
dB	Decibel
Hz	Hertz
Re	Reynolds Number

Acronym	**Definition**
HAWT	Horizontal-Axis Wind Turbine
AFC	Active Flow Control
AEP	Annual Energy Production
IEC	International Electrotechnical Commission
AOA	Angle of Attack
AJVG	Air-Jet Vortex Generator
COE	Cost of Energy
O&M	Operation and Maintenance
BL	Boundary Layer
VS	Vortex Shedding
ATEG	Adaptive Trailing Edge Geometry
TE	Trailing Edge
LE	Leading Edge
VG	Vortex Generators
AJVG	Air Jet Vortex Generators
ROI	Return on Investment
SPL	Sound Pressure Level
TRL	Technical Readiness Level

0 Abstract

EN

The desire to harvest more energy has pushed the contemporary wind turbines to increase their blade spans in order to be able to harness more power from the wind resource. The objective of the following document is to analyze the challenges large scale wind turbines face, and to obtain active flow control solutions that are able to improve their aerodynamic, aeroacoustic and structural performance. To do so, this paper focuses on first understanding the adversities common to wind turbine performance and study their core sources to be able to solve the hindrances with active flow solutions. These are mainly derived from the unpredictable nature of the wind itself, like rapid wind direction and velocity variations, causing aerodynamic phenomena that limit wind turbine's proper performance. These AFC technologies are then researched and discussed, and from the already marketed systems at Technical Readiness Level 9 Air Jet Vortex Generators were picked for their stall and fatigue reduction capabilities together with the annual energy production increase they are proven to provide. To test the implementation and the economical and environmental impact of AFC systems on wind turbine a script model was developed to serve as a guide for the viability of the project depending on the initial cost of investment. Variables used for the model are gathered through the bibliographic research done in AFC systems together with current programs that pursue our very same goal. This tool will aid in the development of the AFC product in order to accomplish the climate goals our society is heading albeit from a sensible economical standpoint.

ES

El objetivo de extraer más energía ha empujado a las turbinas eólicas contemporáneas a aumentar el tamaño de sus palas para poder aprovechar más energía del recurso eólico. El objetivo del siguiente documento es analizar los retos a los que se enfrentan los aerogeneradores a gran escala y obtener soluciones de control de flujo activo que sean capaces de mejorar su rendimiento aerodinámico, aeroacústico y estructural. Para ello, este trabajo se centra en comprender primero las adversidades comunes al rendimiento de las turbinas eólicas y estudiar sus fuentes principales para poder resolver los obstáculos con soluciones de flujo activo. Estos se derivan principalmente de la naturaleza impredecible del viento en sí, como las rápidas variaciones de dirección y velocidad del viento, causando fenómenos aerodinámicos que limitan el rendimiento adecuado de la turbina eólica. Estas tecnologías AFC se investigan y discuten, y de los sistemas ya comercializados en Technical Readiness Level 9 Air Jet Vortex Generators fueron seleccionados por sus capacidades de reducción de stall y fatiga junto con el aumento anual de la producción de energía que se ha demostrado que proporcionan. Para probar la implementación y el impacto económico y ambiental de los sistemas AFC en una turbina eólica se desarrolló un código que servirá como guía para estudiar la viabilidad del proyecto en función del costo inicial de la inversión. Las variables utilizadas para el modelo han sido recopiladas a través de la investigación bibliográfica realizada en sistemas AFC junto con resultas de productos actuales que persiguen nuestro mismo objetivo. Esta herramienta ayudará en el desarrollo de un producto de tecnología AFC para lograr los objetivos climáticos que nuestra sociedad se ha puesto como objetivo, todo desde un punto de vista económico sensato.

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L'objectiu d'extraure més energia ha espentat a les turbines eòliques contemporànies a augmentar la grandària de les seues pales per a poder aprofitar més energia del recurs eòlic. L'objectiu del següent document és analitzar els reptes als quals s'enfronten els aerogeneradors a gran escala i obtindre solucions de control de flux actiu que siguen capaços de millorar el seu rendiment aerodinàmic, aeroacústic i estructural. Per a això, aquest treball se centra en comprendre primer les adversitats comunes al rendiment de les turbines eòliques i estudiar les seues fonts principals per a poder resoldre els obstacles amb solucions de flux actiu. Aquests es deriven principalment de la naturalesa impredictible del vent en si, com les ràpides variacions de direcció i velocitat del vent, causant fenòmens aerodinàmics que limiten el rendiment adequat de la turbina eòlica. Aquestes tecnologies AFC s'investiguen i discuteixen, i dels sistemes ja comercialitzats en Technical Readiness Level 9 Air Jet Vortex Generators van ser seleccionats per les seues capacitats de reducció de stall i fatiga juntament amb l'augment anual de la producció d'energia que s'ha demostrat que proporcionen. Per a provar la implementació i l'impacte econòmic i ambiental dels sistemes AFC en una turbina eòlica es va desenvolupar un codi que servirà com a guia per a estudiar la viabilitat del projecte en funció del cost inicial de la inversió. Les variables utilitzades per al model han sigut recopilades a través de la investigació bibliogràfica realitzada en sistemes AFC juntament amb resultes de productes actuals que persegueixen el nostre mateix objectiu. Aquesta eina ajudarà en el desenvolupament d'un producte de tecnologia AFC per a aconseguir els objectius climàtics que la nostra societat s'ha posat com a objectiu, tot des d'un punt de vista econòmic assenyat.

1 Introduction

1.1 Aim

The aim of the following document is to perform a comprehensive analysis on the challenges horizontal wind turbines face and look for solutions in flow control systems to develop a model able to calculate the economical and environmental impact of the proposed technology's implementation.

1.2 Scope

The scope of the project spans over contemporary horizontal wind turbines (HAWTs) and the most common challenges they present regarding their means of power extraction, aerodynamic behaviour and their subsequent structural and aeroacoustic phenomena. After a deep understanding of these problematic roots, the currently available market active flow control (AFC) solutions to improve their economic and environmental performance are researched and discussed. This will allow for the understanding of the potential of said improvement and then a comparison the bibliography with vast amount of data coming from real-life scenarios.

This research will allow the building of a model able to calculate whether the implementation of the chosen AFC system is sensible or not regarding both its economical and environmental impact after installation in a sample HAWT located in a Spanish wind farm. The study will present different scenarios (optimistic to pessimistic), as well as a comparison between higher-MW turbines with great installed power and their lower powered counterparts under 1000 kW.

As this project aims to be an initial approach into understanding the impact of using active flow control systems in HAWTs, some aspects that could be developed in future projects but are **not** included in the present document are, just to name a few:

- Study differences between onshore and offshore turbines.
- Economical analysis including the initial installation of the HAWT.
- Detailed research on an approximate initial investment.
- Integration of model as a function to calculate larger databases.

These will be briefly talked about at the end of the document with some guidelines to continue the research and building the model in future projects.

1.3 Requirements

After considering the whole document, the reader must get an understanding of the core issues contemporary HAWTs face, as well as their root causes and how can they be solvented by AFC systems. There will be one or a couple of AFC systems selected to try and implement in a real case scenario, at least comparing between turbine models and identifying the underlying variables that affect the implementation scheme of this technology. A functioning R code should be produced as well to test as many different scenarios as the reader desires. To sum it up, the expected outputs of this paper are:

- Understanding of main issues and challenges of HAWTs performance.
- State of the art of active flow control system with bibliographic support.
- Latest improvements and prospects in active flow control systems.
- Understanding of the different cost sources affecting the economical model of a HAWT.
- Comprehensive research on noise pollution and the environmental impact of HAWTs.
- A functioning R code that simulates the implementation of an AFC system inside one (or more) contemporary multi-MW turbine, as well as a whole farm.
- Study impact differences between turbines depending on installed power.
- Extract current challenges and prospects of the scripted model.

1.4 Background and justification

Over the past decades the consumption of fossil-fuel reserves for energy production raised many environmental concerns and the need for less harmful and energy efficient means of power generation, eco-friendly and renewable sources that guarantee global energy security. Many efforts are now focused on developing and optimizing the various renewable energy sources like wind, solar, hydro, geothermal, etc. which are essential to achieve the goals many nations across the world set for the upcoming years.

Nowadays, the rise in fuel costs and the global geopolitics show the impact this uncontrolled fossil consumption and how the system is spiralling out of control if countermeasures like renewables are not set in motion.

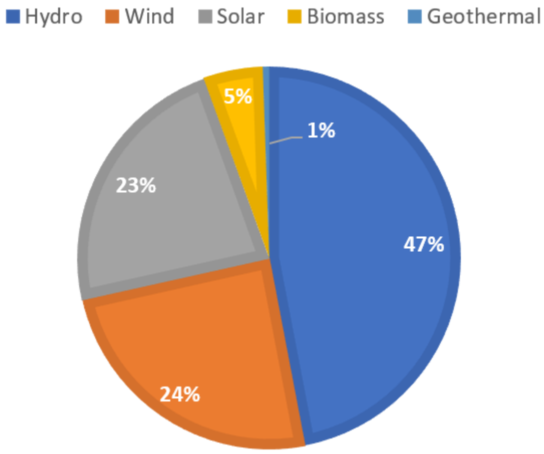

Figure 1: Distribution of Renewable Energy Production in 2019.

The International Renewable Energy Agency established that the Global Renewable Energy capacity in 2019 amounted to 2537 GW, almost 35% of the Net Global Energy capacity [1] where 2.5% corresponded to wind sourced energy. Figure 1 shows a pie chart with the distribution of energy production back in 2019, with an expected growth of 9.2% in the upcoming years. This growth can only be achieved by extracting larger amount of power using larger wind turbines, like the multi-MW turbines nowadays that feature spans of more than 200 m in diamater, like Siemes Gamesa SG 14-222 DD, with 14MW of installed power and a height of 260 m. Just as a comparison, the diameter span of the aforementioned turbine is almost as large as three Airbus 380 placed side by side.

Majority of the expense of these installations comes from their off-design conditions and the structural damages that need to be considered under operation and maintenance (O&M) cost, rendering their Cost of Energy (COE) of kWh produced lower than other power sources. The need for larger turbines and the challenges they face as a consequence of their massive spans calls for solutions that are able to improve their performance and COE and deliver optimal results, solutions like active flow control systems that can help mitigate aerodynamic issues and improve the economical and environmental impact of HAWTs depending on their characteristics.

2 Performance challenges

Contemporary HAWT's are often equipped with blades of large spans with huge swept areas in order to get the maximum gains when extracting power from the wind. The ability of these HAWT's to react to quick changes in wind velocity is obstructed by the huge rotational inertia of the whole rotor assembly with these massive spans, taking also into account the mass of each of the individual blades holding onto their pitch change mechanisms. Even when wind is considered in steady conditions there really are many rapid and significant fluctuations in velocity that pose a challenge to these big blades.

This inability of the system to adapt its angular velocity to that of the complete rotor system is understandable once we see the spans of some wind turbine rotor specifications collected below on Table 1.

Turbine	Power (kW)	Rotor diameter (m)	Swept area (m^2)
Siemens SWT 6-0-154	6000	154	18.2
Gamesa G-136	4500	136	14.5
Enercon E-136	7500	127	12.7
GE 4.1-133	41000	113	10
Siemens SG 14-222 DD	145000	222	24.9

Table 1: Size sample of various multi-MW turbines.

To further understand the challenges a wind blade turbine might face when using the wind as a resource, the three main problems derived from the aerodynamic behaviour are rapid wind velocity fluctuations, vertical gradients that may appear from uneven topography and wind direction changes.

2.1 Energy source issues

- **Wind direction changes**:

  The wind resource usually has sudden direction changes that pose a threat to the proper functioning of the HAWT. Taking Catalunya as an example even though it is a low gradient area when compared to other wind farm locations, in Figures 2 and 3 [2][3] the wind direction can be erratic most of the times, having usual operating wind directions that can suddenly change and require adjustment.

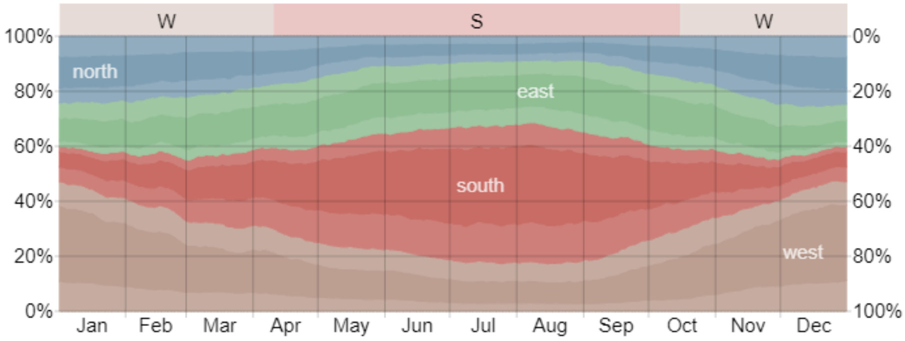

Figure 2: Yearly distribution of wind direction in Barcelona. [2]

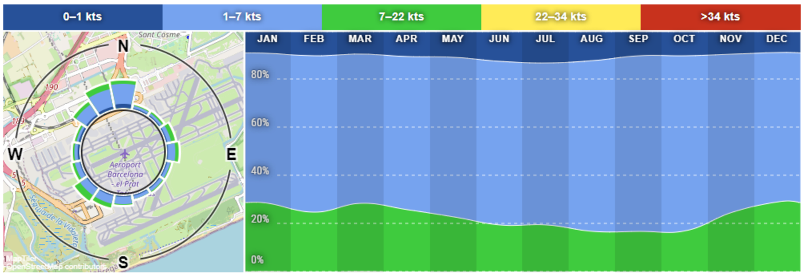

Figure 3: Barcelona-el Prat airport wind direction gradients. [3]

These changes in the azimuthal direction can be compensated by the yaw mechanism of the HAWT's but not at a satisfactory response time when comparing to the time frame at which these wind velocity changes occur, mainly due to the aforementioned huge mass that is mounted on top of the rotor mechanism.

- **Wind velocity deviations**:
  A study performed on a Vestas V164 [4] was set to study the nature of the wind velocity, with the standard deviation given in the standards set out by the Electrotechnical Commission (IEC) [5] and shown below as Equation 1. Using a value of $b = 5.6\ m/s$ and the values for the Vestas registered in the IEC this yielded a standard wind deviation of 1.939 m/s, setting the margin for the 11 m/s set as its annual average wind speed.

$$\rho_I = I_{ref} \cdot (0.75 V_{hub} + b) \tag{1}$$

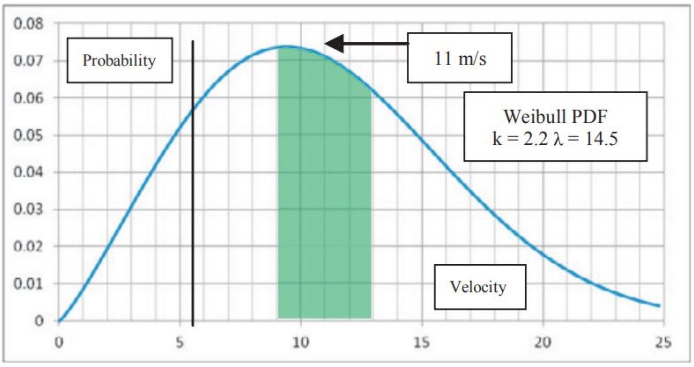

Figure 4: Weibull distribution of wind ω with annual avg. v [4]

The probabilistic continuous Weibull distribution of the wind velocity plotted above on Figure 4 together with this 11 ± 1.939 m/s optimal operating range suggests that the chance to be inside this margin is 27.21%, which means that the mere size of these blades together with the rotor assembly makes it difficult for a HAWT to respond in a satisfactory manner to these fluctuations either by trying to shift the blades pitch or by adjusting the rotors angular velocity to the current changing conditions.

- **Vertical wind gradients**:
  When HAWT's are located in bigger wind farms more complications arise due to interactions with the local topography. Again, using the same Vestas study with a hub height of 100m and a wind velocity of 11m/s, together with velocity gradient calculations from the IEC, a Figure 5 is plotted to show the consequences.

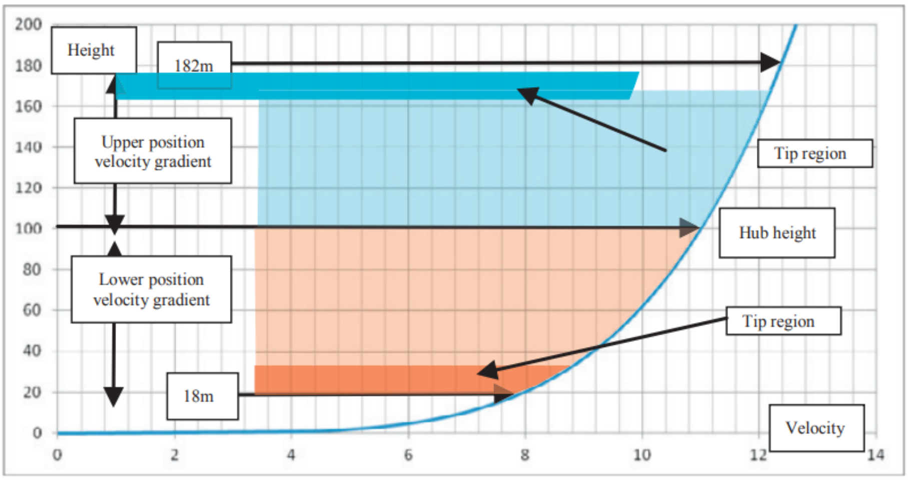

Figure 5: Vertical wind gradient distribution [4]

As seen on the image above the most relevant aspect of this phenomena is the velocity gradient across the span of each blade, as it is rotating from vertical upwards/downwards position, changing the tip velocity from maximum to minimum values of the gradient range. Similar behaviour is happening along the rest of the wingspan although at lesser degrees.

Finally, to add to the general issues a HAWT might face when extracting energy from the wind, the disposition of these machines has to be taken into account as they usually operate among a group of other HAWT's in wind energy farms. Those HAWT's operating on the wake of other machines upwind from them might experience even greater condition disparities. [6]

The fact that the huge blades of the HAWT's are so susceptible to rapid changes in wind conditions has an effect on their performance, noise generation and structural integrity. All these have aerodynamic phenomenon as a root cause, primarily due to dynamic stall. Any delay when responding to changing wind conditions can lead to a partial stalling (non dynamic stall) of the turbine blades, resulting in a potential loss of power extraction and aeroacoustic phenomenon. However, the inability altogether to respond in a satisfactory manner to rapid changes on wind conditions can lead to a dynamic stall, where under its conditions it is subjected to rapid fluctuations of lift and moment coefficient, having a significant impact on the structure of the turbine blades due to fatigue issues.

2.2 Stall and fatigue

Dynamic stall is a non-linear unsteady aerodynamic phenomena related with cyclical changes in angle of attack (AOA) associated mainly with helicopters and flapping wings, but due to the gusting airflow, rapid variations and the steady angular velocity of the turbine rotor, it also commonly occurs on wind turbines. This type of stall is characterized for the creation and shedding of vortexes (Dynamic Stall Vortexes or DSV) created at the leading edge of an airfoil under rapid changes of AOA. [7]

The shedding and advection of these DSV along the airfoil's chord produces large spikes in lift coefficients (c_L) that come with a significant and rapid variation in moment coefficient (c_M) as well, which when paired together pose as a structural threat that can become a large problem when dealing with the large blades associated with modern HAWT's [8].

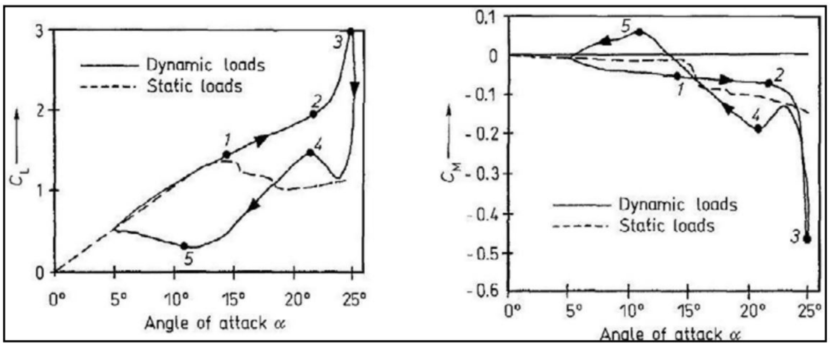

Figure 6: Dynamic and non-dynamic stalls behaviour of c_L and c_M [9]

Above on Figure 6 both types of stall are represented plotting c_L and c_M vs AOA. As seen, the non-dynamic stall has a smaller magnitude of coefficient variations due to the fact that no DSV are generated. Either dynamic or non-dynamic stall are heavily influenced by this phenomenon of flow separation, and that is why techniques of flow control can be the solution to reduce the detrimental effects that stalling has upon modern HAWT's, like fatigue.

Fatigue is a consequence of the blade's being continuously exposed to switches between compression and tension during rotation. Each of this cycles adds to the total fatigue count or ring flow count [10] where a certain amount of fatigue load will have reduced a blade's lifetime by a certain percentage. As the blade gets longer and heavier, they all get faster tip speed involving a lot more forces in the system. For instance wind direction changes, as previously discussed, submit the blade to rapid fluctuations of pressure distributed in a chaotic fashion even on short periods, like shown in Figure 7 below.

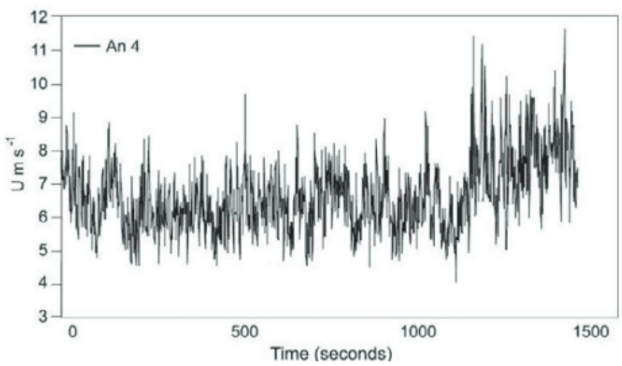

Figure 7: Short-term instantaneous wind velocity [11]

The most common manifestations of fatigue wear are in the form of cracks forming around the trailing edge along the direction of the blade. If this fatigue cracks are not detected soon enough, they would expand radially and transversal through the blade. Apart from that, imperfections on the blade can also develop fatigue effects that have to be taken care of. All of the aforementioned issues, plus the unstable aerodynamic nature of the blade puts the system into a harsh environment that has to be taken care of with predictive and, more often than not, corrective maintenance. The latter type of maintenance occurs when the fix comes after the issue has already happened and the system becomes severely damaged by it. Returning to its optimal state might even be rendered impossible, shortening the blade's lifespan and thus making the whole HAWT's slowly deteriorate.

Looking for methods that alleviate loads like vibrations, blade root bending moment and overall stall to avoid exposing the system to fatigue issues will greatly improve the behaviour of the wind turbine, not only performance-wise but also from the economic standpoint.

2.3 Aeroacoustics

Noise generated by a wind turbine generally has two different sources: mechanical and aerodynamic. Mechanical noise is generated from various moving machinery components inside the turbine's nacelle like generator, fans, gearbox and other devices. This type of noise is primarily tonal, which means that the noise generated peaks at certain frequencies that result harsher than broadband noise. To suppress this kind of noise many solutions exist like shielding the nacelle with sound absorbing materials, vibration suppression techniques [12]. In this section, however, the focus will be set on top of noise derived from aerodynamic phenomena, which is a dominant source in the whole noise spectrum generated by the HAWT.

Figure 8 below shows the individual contribution of different aerodynamic noise sources at different frequencies, some of them originating from the interaction of the incoming flow with the profile or due to the airfoil itself.

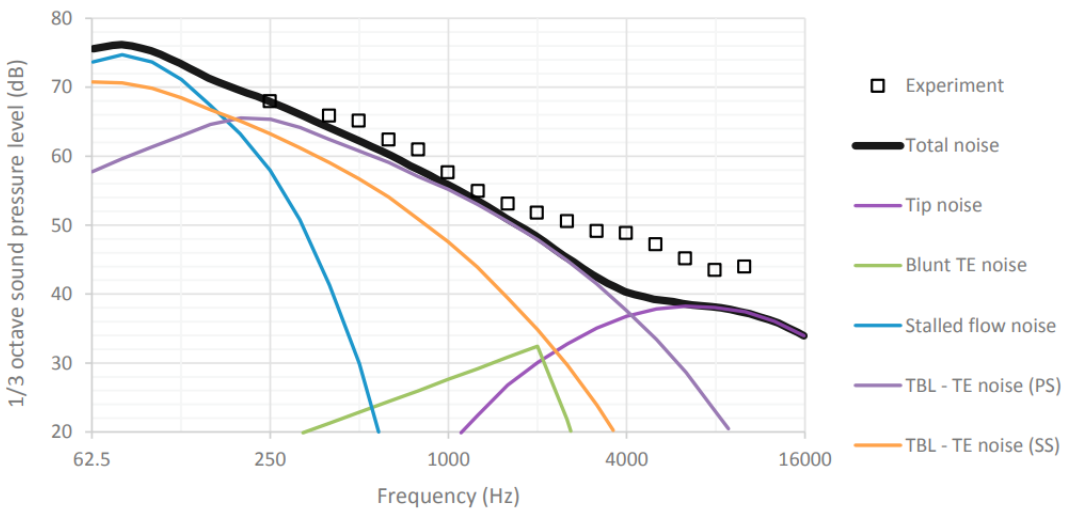

Figure 8: Contribution of different aerodynamic sources of noise in a WT. [12]

- **Tip vortex formation** noise is a product of the interaction between the viscous turbulent core tip vortex with the TE near the tip [12]. This tip vortex is formed due to a cross flow generated by the pressure difference between pressure/suction side, and since it lies on the high frequency region of 1-4 kHz, where humans are more perceptible, it is an important contributor to overall aeroacoustic noise.

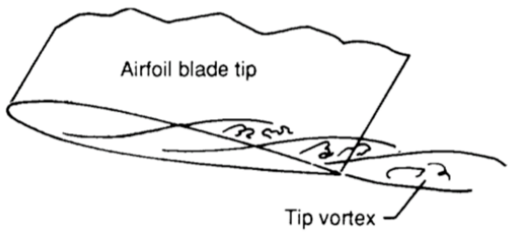

Figure 9: Tip vortex formation phenomena [13]

- **Blunt trailing edge** (TE) noise happens when vortex shedding occurs at blunt TEs, where the frequency is dependant of the thickness and proportional to velocity. This results in a tonal noise emission seen as a sharp peak in the noise spectrum as seen above in the green line of Figure 8.

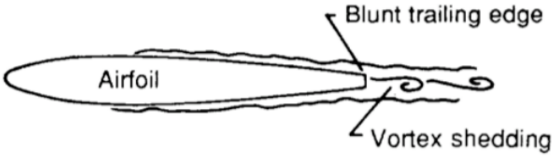

Figure 10: Blunt trailing edge vortex shedding [13]

- **Stalled flow** noise is the result of the aforementioned stall effect, when after a certain AOA the flow separates, becomes unsteady and causes broadband noise emission. Stall mitigation is the main tool to avoid this kind of noise.

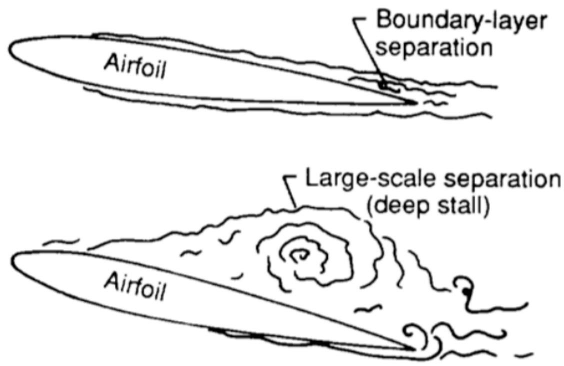

Figure 11: Stalled flow after BL separation [13]

- **Turbulent boundary layer** trailing edge noise (TBL - TE) is a dominant noise source that occurs when the turbulent boundary layer interacts with a sharp TE. At low Mach numbers turbulent eddies are inoffensive along a flat plate, but when facing a sharp edge they become great noise sources that radiate into the atmosphere [12].

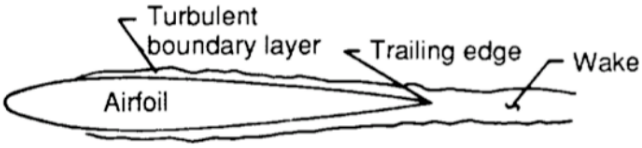

Figure 12: Turbulent BL exiting TE [13]

- **Laminar boundary layer** vortex shedding noise (LBL - VS) happens when both sides of the airfoil reach the TE while remaining laminar, most likely due to a small Reynolds number ($< 10^6$). The noise from this source is "coupled to acoustically excited feedback loops happening between instability waves and the trailing edge" [13]. This phenomenon can be avoided by tripping the BL far upstream from the TE [12].

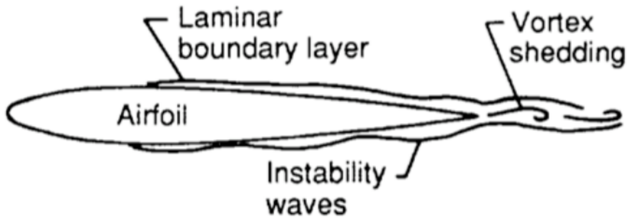

Figure 13: Laminar BL shedding noise [13]

There are a great number of adaptive noise reductions approaches to suppress aeroderivative noise but most of them imply a reduction in annual energy production (AEP) i.e. power output. One of these methods is to vary the rotation speed of the blades, since velocity is proportional to noise production. A reduction would mean less noise but also a decrease in AEP so it should only be implemented in a certain range of velocities. Other solution would be trying to increase pitch angle and reduce the AOA, making the size of the turbulent BL on the suction side smaller and thus reducing noise generation in the wind turbine which is considered one of the strongest sources of noise production [13]. However, reducing the AOA means that less power output is generated.

As an alternative to the aforementioned methods, other adaptive solutions like flow control devices could be the solution to mitigate most of the aerodynamic sources that cause noise pollution. Each system is expected to target a different phenomena depending on the way they approach solving the issues discussed along this chapter. Further into the document these technologies will be assessed and discussed to get a grasp of their potential.

3 Flow control devices

Contemporary multi-MW wind turbines operate several hundred meters from ground, where the atmosphere there is more prone to experience many aerodynamic phenomena, increased turbulence, local gust-induced fluctuations, interference, tilt/yaw misalignment and wind shear, just to name a few. Due to the massive size of these blades attracted by gravity and generating periodic structural loads and vibrations, many manufacturers are looking for ways to overcome these issues, like the use of variable speed and individual pitch control rotors. These allow the turbine to operate closer to the maximum aerodynamic performance at a wider range of speed conditions, and thus being able to extract more energy from the wind resource.

A solution for many of these shortcomings can come from the aforementioned control mechanism of load alleviation and fluctuation dampening, effectively increasing the harnessing of power and ensuring blade integrity. Improvement the aerodynamics and aeroacoustics performance of the blade is possible by means of active flow control, all while attempting to mitigate structural loads (extreme and fatigue) [14], whether it be by advancing/delaying transition, utilizing turbulence and promoting/preventing flow separation. There are many strategies to follow when approaching flow control, and the two main schemes that exist are passive and active flow control.

- **Passive flow control**: ranging from broad geometry changes to small mechanical structures, their aim is to shift the pressure gradients over the blade to enhance the aerodynamic response [15]. There are many different strategies that stem from the moment the blade is designed, and these techniques are often paired with other active flow solutions to get the best performance.

- **Active flow control**: this devices are able to selectively manipulate the flow around specific positions of the blade in response to the local variations in the flow and manifesting adverse blade loading, bringing this wind conditions back to a desirable effect. There are various examples of active flow control devices, for example; trailing edge flaps or microtabs for wind turbines, trailing edge synthetic jets for circulation control, air-jet vortex generators on the surface of the blade and plasma actuators to control aerodynamic loading and separation.

In both groups, the use of microprocessors are focused on processing sensor-feedback and apply integrated control algorithms to command local actuators, improving the system response [16]. Different active flow control systems will be presented in the remaining sections of this chapter, many of them tested upon a NREL 5-MW model wind turbine used for many computational studies regarding performance improvement in wind turbines, with its dimensions and morpohology shown below on Figure 14.

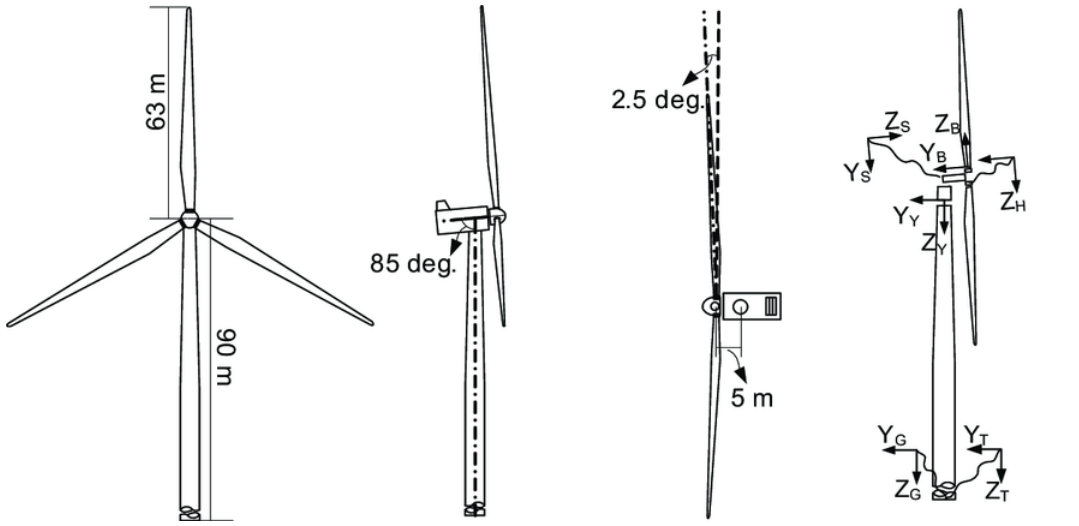

Figure 14: NREL 5-MW wind turbine model for computational analysis. [17]

It must be noted that flow-control derived enhancements are not mutually exclusive and they are best combined in particular cases and therefore the selection of flow-control devices depends completely of the particular case of study to achieve the best performance optimization with minimal trade-offs. As a final remark, active flow control requires an external energy source to be able to operate and, therefore, the up-comings of the technique in terms of increase in power output or blade lifetime must offset the external energy or additional capital/-maintenance costs required for flow control.

3.1 Flaps

Flaps are moving aerodynamic surfaces that are hinged on a blade to vary the profile's chamber and in this way tailor the aerodynamic performance, modifying the chordwise pressure distribution [18] and enhancing the lift. The use of these devices in wind turbines dates back to the 1990s, when the research effort on flap-based control systems made by the National Renewable Energy Laboratory (NREL) focused at achieving performance enhancement with flow transition delay [19, 20], flap assisted power regulation and aerobreaking [21, 22].

Potential for load control and power augmentation was proven in many numerical analysis and experiments, one of those reporting 20-50% reductions in root load [23], and another tested on a reference NREL 5-MW turbine that proved a 12% reduction in blade-root bending moment and tip deflection [24]. Furthermore, a combination of individual pitch control paired with active flap deflection was tested and proven to alleviate loads both on the blade and on the rotor hub and tower [25]. After all the research it was proven that flaps were effective in power augmentation and load alleviation while maintaining steady power generation [26] and reducing the levelized cost of energy (LCOE). [27]

The latest in flap technology allow these mechanisms to employ passive activation like inertial-driven flaps [28] and mechanical-driven ones consisting of dampers, springs and inverters that measure the angular velocity to then generate the right amount of torque [29]. All in all, these mechanisms were proven to be effective in a great reduction of load stress and deflection, and nowadays exist many similar alternatives that come tailored with specific advantages, like the Adaptive Trailing Edge Technology (ATEG) and the Gurney flaps. Figure 15 groups all these in a sample distribution of how they would all fit inside the blade span.

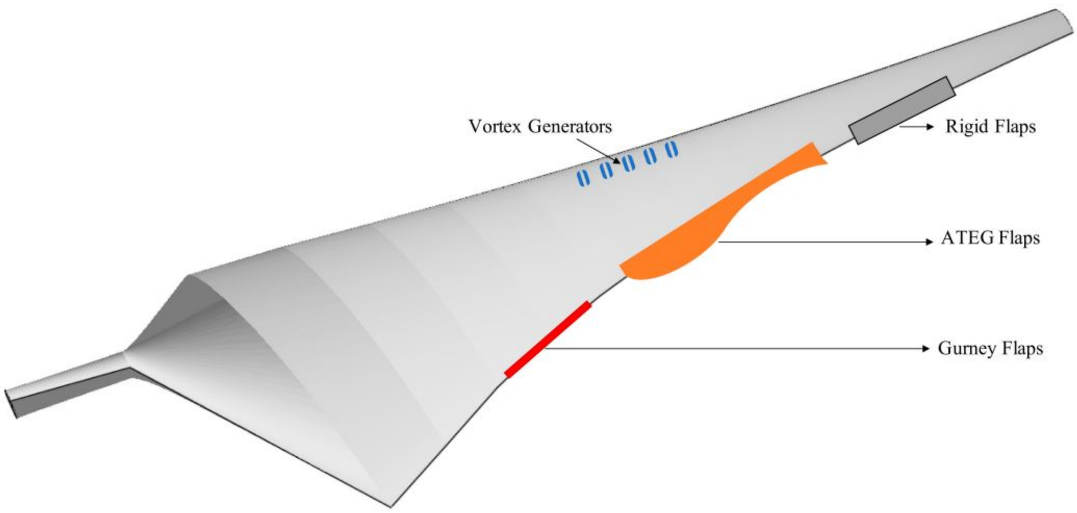

Figure 15: Various flow control devices illustrated atop a wind turbine blade. [30]

3.1.1 Adaptive Trailing Edge Geometry (ATEG)

Figure 15 illustrates how the adaptive trailing edge geometry is generated with mechanisms that manage to get an efficient chamber control. This concept alters the Kutta condition of the airflow, thereby enhancing the lift in off-design conditions by changing the camber line, especially useful when talking about wind turbines and their aforementioned issues.

When compared with regular flaps ATEGs require 30% less deflection to archive similar aerodynamic enhancements [31], with studies suggesting that the reduced fatigue loads they provide are due to the alteration in the flow interactions with the blade at its main load frequencies, effectively attenuating said loads [32]. Testing this technology on the same NREL 5-MW reference turbine as the flaps in the previous section, resulted in a 13% reduction in blade-root bending moment (1% more than flaps) with a successful suppression of the critical component's relative motion of 30% (std. deviation) [33].

3.1.2 Gurney flaps

Named after Dan Gurney, the man who developed this system back in the 1970s by mounting flat plates perpendicular to the profile on the trailing edge aiming at load alleviation and performance enhancement. This can also be seen located on Figure 15. Their performance impact stems from the creation of counterrotating wake vortexes that energize the boundary layer and mitigate flow separation, shifting the stagnation point further downstream of the TE and enhancing lift performance. Figure 16 illustrates this phenomena. Active flow control systems using Gurney flaps are demonstrated to have significant load alleviation as they presented a reduction of 70% in aerodynamic lift and blade alleviation according to simulations carried out on the reference NREL 5-MW turbine [34]. Application of Gurney flaps on this same wind turbine managed to enhance their power coefficient and output power. [35]

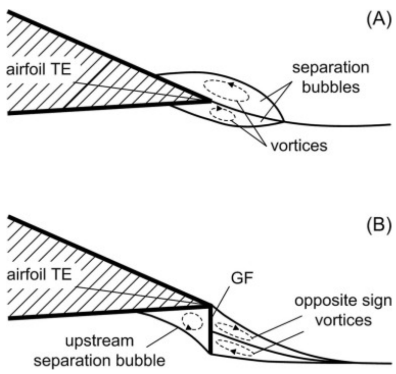

Figure 16: Gurney (B) vs no gurney (A) wake phenomena. [34]

This vertical profiles mounted on the TE managed to diminish the intensity of turbulence, downwash and recirculation; as well as delaying the stagnation point further into the edge thus reducing the average chamber line of profile. All in all, Gurney flaps are effective to delay stall and alter the aerodynamic loads to avoid fracture by fatigue due to wind gusts approaching the turbine.

3.2 Microtabs

Microtabs are small tabs placed perpendicular to the blade's surface near the trailing edge (TE) independently of the airfoil's side. The microtab operating principle is to modify the trailing edge (TE) circulation (Kutta condition) by altering the camber and shifting the stagnation point. The deployment of this devices on the pressure side enhances lift by leaving a recirculation zone in the tab-wake of the suction side [36]. Deploying the microtab on the suction side like shown below on Figure 17, however, promotes lift reduction.

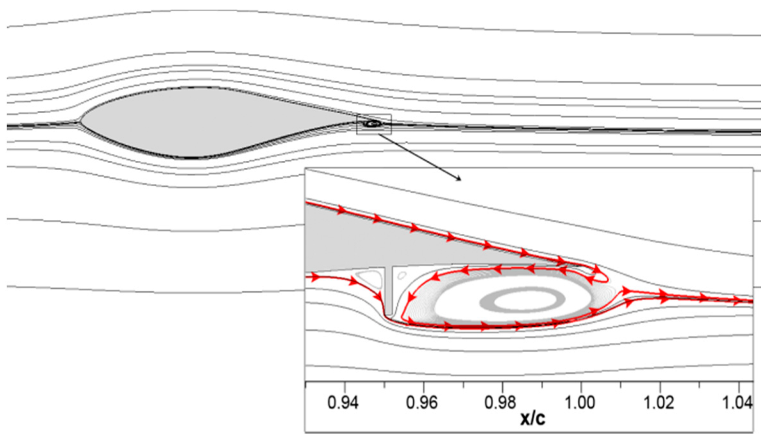

Figure 17: Microtab mounted on top of suction side of blade. [37]

Research has pointed out the potential of microtabs for load alleviation, installing tabs on both sides of the TE and reporting significant load control up until larger AOAs, becoming ineffective [38]. Blade loading after the implementation of microtabs in the model NREL turbine showed an increase in blade-root bending moment and a reduction in peak root-bending moments and tip deflections of up to 70% [39], demonstrating the potential for load control of active microtabs. This technology can also aid in flutter control and suppression [40], with an evolution towards bigger tab-heights (usually 2% of chord length) and more forward positioning to increase effectiveness.

3.2.1 Miniature trailing-edge effectors (MiTE)

The already demonstrated capabilities of microtabs include effective flutter supression, load control potential and lift coefficient increases that can be promising in performance enhancements for aerospace applications. All of the above can be further improved with the use of miniature trailing-edge effectors (MiTEs) originally designed for aircraft applications.

These effectors are small TE devices of approximately 1-5% chord in height that, with a proper activation system, can be set in different control modes: positive with flaps on pressure side, negative with flaps on suctions side or neutral with flaps at neutral position. Figure 18 show the placement of MiTes attached to different TE geometries.

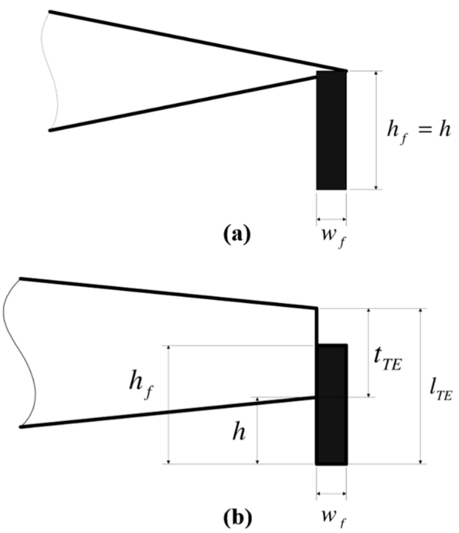

Figure 18: MiTEs geometry attached to a (a) sharp and (b) blunt TE. [37]

This technology demonstrated particular improvements on wake-vortex alleviation [41], rotor vibration and noise reduction [42]. However, the mandatory blunt trailing edge this AFC system requires increases noise in the tip region and is overall detrimental to the performance of the HAWT when the system is not deployed [36].

3.3 Blowing-Suction control

Blowing-suction control consists in re-energizing the boundary layer to maintain an appropriate adverse pressure gradient and delay stall, by means of injecting high momentum air mass into the flow-stream reversing the boundary-layer friction deceleration and delaying separation. This allows for a stall extension and improved lift performance [43]. The other method involved in this systems is sucking low momentum fluid that is in risk of separation, replenishing the free stream and energizing the boundary layer leading to enhanced performance [44]. This method requires to drill holes in the profile where the air mass flow can be either blowed/sucked, placing these slots upstream of the separation point. A combined actuation of all the devices at the LE and TE allows for the most optimal performance, however having multiple slots on the airfoil augments the effective surface and therefore, drag, an effect prominent at higher AOAs.

The application of blowing slots can extend to wind turbines [45], achieving up to 60% lift enhancement and successful stall extension and drag mitigation. Studies like [46] demonstrated a power coefficient increase of 2.5 in smaller turbines with lower installed power (0.5MW). The extents of blowing-suction technology go beyond an AEP increase for wind turbines, but can be effectively used for noise mitigation and load reduction.

Aerodynamic load control with the blowing mechanism, like in the form of pulsating jets, reduced fluctuating loads thanks to boundary layer extraction (suction) and energizing (blowing), unsteady shear-layer generation and streamwise vortexes. Other methods like adaptive blowing allowed to effectively suppress stall and achieve nearly constant phase-averaged lift and mitigated unsteady aerodynamic loads [43]. Passive blowing on the other hand can be ideal for load alleviation and reduced blade root bending moment and tip deflections [43]. Some proposed blowing circulation control approaches are shown below on Figure 19. [47]

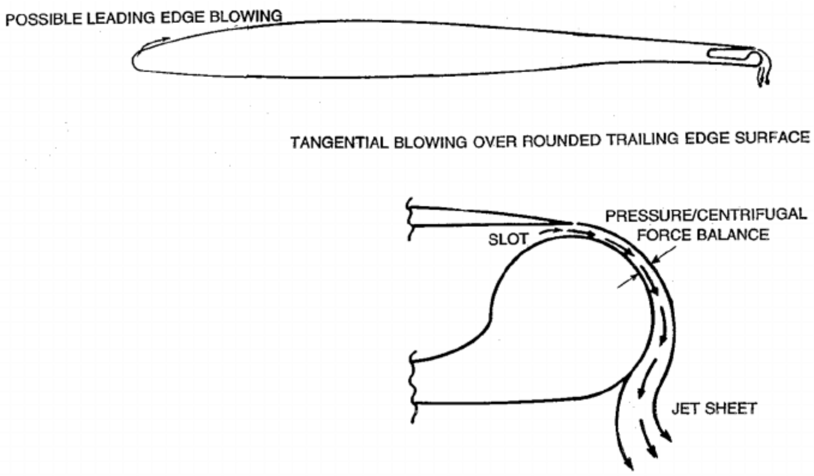

Figure 19: Blowing circulation control mechanism on LE and TE. [47]

Regarding aeroacoustic noise mitigation, blowing steady jets into the wake vortexes achieved noise suppression up to 16 dB [48]. This is due to jets rendering the wake into smaller vortexes blown further upstream by jet momentum, ultimately losing negative vorticity due to recirculation and thus reducing noise-levels. The thinning of the boundary layer can lead to noise attenuation of up to 3.5 dB [48] in applications on the NREL 5-MW wind turbine with an AEP enhancement of 2%. Another study [49] carried out on the N117 industrial wind turbine revealed aeroacoustic noise suppression of 3.6 dB with 4.75% increase in total AEP, but beyond a noise attenuation of 5 dB the turbine performance started to degrade due to hardware limitations. This is a compromise that must be taken into account when installing blowing-suction control mechanisms or other pulsed actuators solutions, where noise mitigation (and noise production by the systems themselves) can compromise other advantages like stall-avoidance and lift increase (power generation).

3.4 Plasma actuators

Plasma actuators are composed of a pair of electrodes (anode and cathode) that generate an electric field and induce wind near the surface by wiring them with a large voltage difference. This 'ionic-wind' is generated by the impact forces between the electrode gap area of plasma ions and neutral air particles [50]. The induced wind acts as a body force pushing the surrounding fluid, modifying the airflow profile on the boundary layer and effectively postponing its separation. Figure 20 shows a corona discharge actuators, one of the first plasma actuators used for flow control. [51]

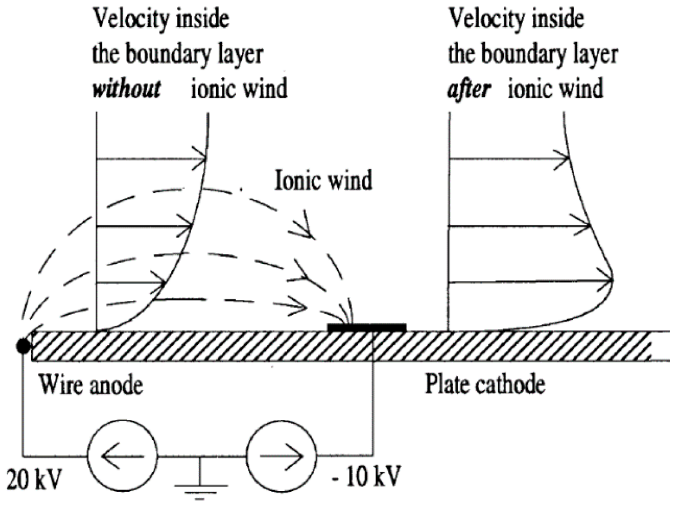

Figure 20: Ionic wind impact of corona discharge actuator. [51]

In regards of load control applications, plasma actuation arrays exhibited great load controllability for low velocities in a free-stream where a mix of actuators excited in different modes successfully improved flow stability and mitigated aerodynamic load, alleviating blade fatigue loads enchancing the blade's aeroelasticity and thereby reducing O&M costs.

Another particular application of plasma actuators is vortex-shedding suppression, like in [52] where effective vortex supression from a blunt trailing edge achieved an energy reduction by a factor of six in the shed Von-Kármán modes. Not only that, this technology can also act as vortex generators, producing comparatively stronger vortices than vane-type vortex generators (VG) discussed in the next chapter, proving to be very useful in the control of the wind turbine's rotating stall [50].

Using plasma actuators for enhancing wind turbine's performance is a sensible choice not only for the aforementioned rotating stall mitigation but also due to almost a 25% torque reduction due to drag and stall suppression. Testing this technology on a sample 1.75MW turbine demonstrated its effectiveness due to the effective suppression of flow separation that yielded a 5% increase in AEP [53]. In addition, plasma actuators are also shown to be practical deicing solutions for wind turbine blades [54].

3.5 Vortex generators (VG)

Vortex generator systems are composed of small vanes mounted on the suction-surface incident to the flow around the blade. A momentum shift from the stream into the inner-flow zone is carried out by the VGs, generating trailing vortexes that penetrate further against adverse pressure gradients before separating, reengergizing the boundary layer and delaying flow separation.

This flow separation of the boundary layer happens when there is flow reversal, and in the stall conditions studied earlier this point is characterized by null shear stress. This mechanism promotes the invasion of fluid into the boundary layer from the free stream and effectively enhances the overall lift coefficient. VGs can be co-rotating or counter-rotating, with the latter being more effective as they add more momentum and strengthen the surface flow more effectively, especially on post-stall conditions. [55] An example of a VG array mounted onto a wind turbine blade can be seen below con Figure 21.

Figure 21: VG array mounted onto an actual wind turbine blade. [56]

From the first time they were implemented back in the 1940s they demonstrated and increment of 20% in Annual Energy Production (AEP) for Mod-2 and Mod-0 turbines [57] and an increment of 15% AEP for a 2.5 MW (Mod-2) HAWT [58]. This aerodynamic performance enhancement was proven further in other studies, demonstrating a 25% increment in lift coefficient [59] for a stall delay of 6 deg. Smaller VGs seemed to perform better than larger counterparts, a finding consistent throughout many studies that paves the way for new research areas that will be further discussed.

Alongside these aerodynamic enhancements, performance enhancements and power augmentation in wind turbines have also been documented. An increment of 10% was proven on a 10-MW turbine with particularly rough blades [58], demonstrating its success for blade soiling mitigation on wind turbines. Wind turbine blade soiling is a surface contamination problem where foreign objects impinge on the leading edge during blade rotation. These foreign objects like mud, salt, dust, dead insects or other airborne objects accumulate on the blade surfaces and can cause adverse flow behaviour. The integration of VG systems on the test wind turbine NREL 5-MW enchanced its AEP from a 6% loss due to flow separation and blade soiling to a 1% gain in AEP [60]. Adding Gurney Flaps to the configuration as well proved to obtain an overall power generation increment of 10% on the same turbine [58].

Now, after detailing the technology behind these systems, it is necessary to know all the variants that work on top of the demonstrated success of VGs. Many variations of the latter exist that aim to improve in certain areas to improve performance enhancement, maintainability or energy savings.

- **Miniature Vortex Generators (MVGs)**

  Miniature VGs are able to better delay flow separation at low air speeds [61] with reduced parasitic drag in comparison with their small size. However due to their small dimensions the votexes generated are weaker in comparison, so they need to be place in optimal positions taking into account their orientation as well.

  Experimental results demonstrated a superior drag reduction capability, with an 8% more reduction than regular VGs (30%) [61]. The smaller vortexes are proven to be useful at these low Reynolds number conditions but since the operating range of the incoming airflow might vary outside of this values, further investigation is needed for them to be able to compete at level with other VG systems.

- **Smart Vortex Generators (SVGs)**

  Enabling these systems to become active and react accordingly to the incoming flow could tailor lift enhancement and stall delay, experimentally demonstrated to increment 0.16 in lift coefficient and a stall delay of AOA [62]. Similar to these SVGs, high frequency miniature vortex generators (HiMVG) operate at higher frequencies and produce periodic vortexes, and their separation control potential under turbulent condition was proven with their dynamic deployment being more effective than static operation.

3.5.1 Air Jet Vortex Generator (AJVG)

Differentiating from regular VGs, air jet vortex generator (VGJ) project airstreams into the crossflow through the blade profile to generate streamwise vortexes throughout the boundary layer, carrying all the high-momentum flow toward the surface and preventing separation. This high energy fluid introduces sluggish boundary layers with more momentum, allowing them to further penetrate against contrary pressure gradients before separation. Stall delay and lift augmentation are also observed when using this kind of devices.

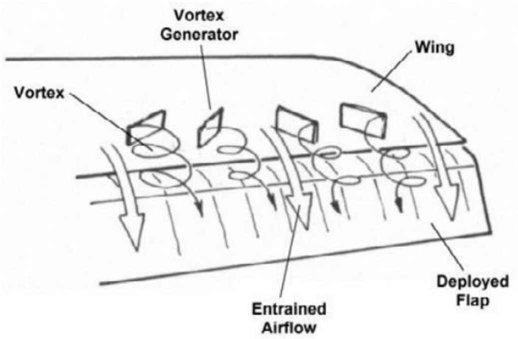

Figure 22: Fixed vane vortex generators (VVG) [63]

Applications of this system in a passive way would involve the use of fixed vane vortex generators (VVG) shown in Figure 22, that have the advantdge of being simpler but at the expense of not being always able to provide the instantaneous responsive control needed to mitigate the symptoms leading to dynamic stall. On the other hand, AJVGs replace these VVGs with a series of small air jets like to ones shown in Figure 23 that are more complex but allow for a more rapid response and are overall a better separation control devices demonstrated both in cyclical and non-cyclical changes in AOA.

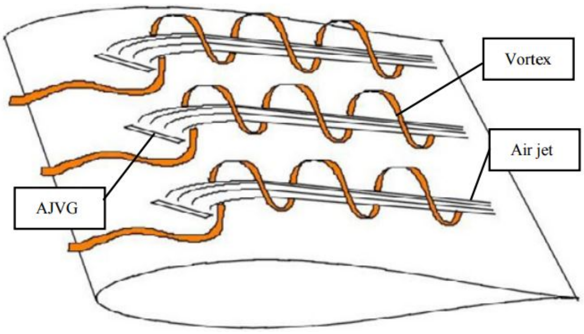

Figure 23: Air jet vortex generators (AJVG) [63]

Experimental studies are testing the use of the exponential jet of Eroglu and Breidenthal [63] used as an AJVG, demonstrating increases in lift coefficient for less energy input (C_μ) when compared to more traditional methods. The main features of this new disposition are an injection width that increases by a given factor and a fluid injection profile that also increases by the same given factor of e (2.71828), like the one shown below on Figure 24. The vortexes generated with this system penetrate better and much further into the crossflow at a reduced mixing rate with the surrounding fluid due to the exponential parameters introducing high-momentum jet fluid into the vortex preventing early debilitation of the structure due to entrainment of low-momentum crossflow fluid. [64]

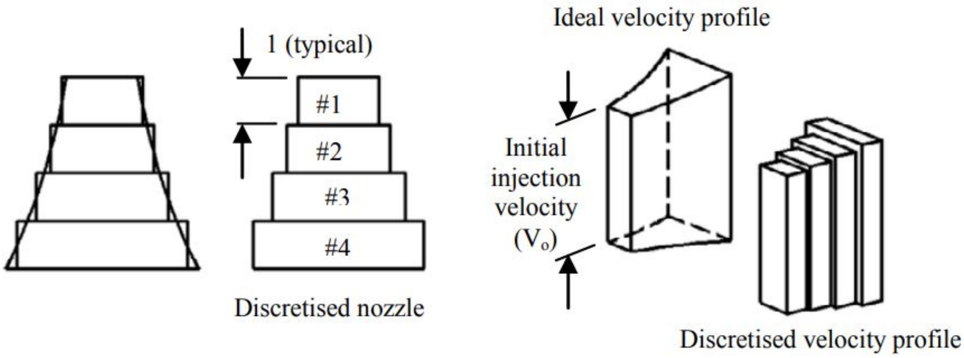

Figure 24: Exponential nozzle and velocity profiles for AJVG injectors. [65]

AJVGs were proven to effectively increase the net power production when used in big HAWTs, maximizing their efficiency by configuring the devices with selective pitch and skew angles of the jet axis [55], as well as the orientation and orifice shape and configuration [57], all depending on the particular conditions of the wind turbine or the focus of the performance improvement. The significant lift enhancement and stall delay capabilities, together with their potential for improving the AEP especially in off-design conditions makes AJVG a great contender for our case study developed on the following chapter.

4 Implementation study

This chapter will focus on the development of a comprehensive, bibliographic research-based model to study the impact of the best active flow control system that can be installed atop a currently running HAWT to test its economical and environmental impact. First, an AFC system will be picked, their current possibilities discussed and then implemented into the model. Afterwards a walk-through of the script's coding will be developed before the results' discussion.

4.1 Active Flow Control discussion

After the comprehensive bibliographic research of the previous chapter, it is clear that there are many flow control options to optimize the performance of modern multi-MW wind turbines. Although they demonstrated great improvement capabilities all of them surely come with shortcomings whether it be performance or cost. These challenges have to taken into account before deciding which flow control system we wish to integrate into our implementation case study.

The success and performance improvements of the AFC systems are highly dependable on the outside conditions, be it wind gusts, temperature, nature agents, and mainly whether the HAWT is intalled onshore or offshore. Most of the previous bibliography was for onshore (on land) turbines, including those researched on the case study. As offshore wind farms get more common some variations in the technology can be expected as a way to adapt to the very different conditions where no wind gradients due to land are expected but wind gusts and external agents might be more prominent.

Flaps, for example, are dependant on size, adding an extra weight and drag penalty to the system. Moreover they are can not be deployed in extreme conditions, as sharp changes in the chamber has a detrimental effect on the glide ratio [21]. Like with ATEGs, they also are prone to mechanical wear and aeroacoustic noise production. ATEG deployment requires a high energy investment, and aside from the powering drawback they may also be prone to creep and degradation over long-term applications that can limit their performance. Lastly, Gurney flaps demonstrated that they are a great addition to any flow control system as a supplementary performance enhancement device.

Challenges associated with microtabs include aeroacoustic noise, flow leakage and complex integration. As previously discussed, MiTEs require blunt edges which have poor aerodynamic performance and higher noise pollution. Plasma actuators on the other hand have the primary limitation of their sensitivity of the flow characteristics, being rendered ineffective beyond $Re = 10^5$ [53], apart from the high maintenance costs required for a stable ionic-wind for all conditions. Blowing-suction mechanisms have issues with the incorporation of the actuation system into the blade, which is a costly process that requires redesigning to reduce weight and system complexity while ensuring structural integrity.

The primary disadvantage VGs have is the increment of parasitic drag they produce under attached flow conditions, which is not optimal in regards to blade performance and power extraction. Minimizing this drag effect could increase the AEP production and limit the noise produced by the vortexes as well as the slots carved in the blade geometry.

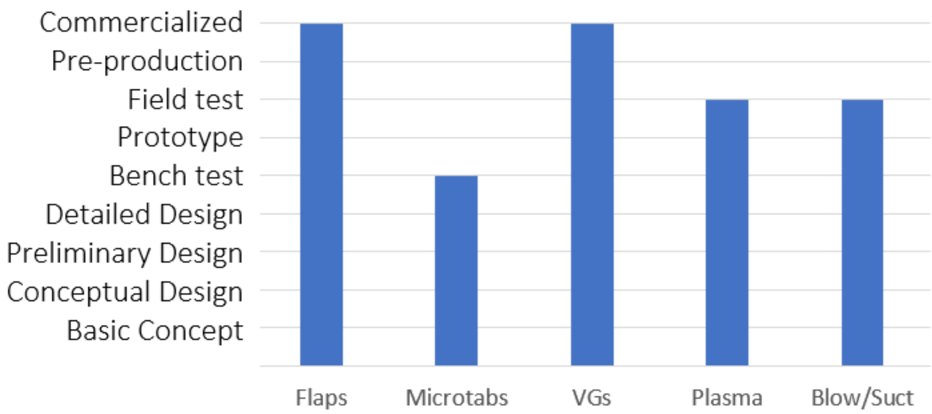

Figure 25: Technology Readiness Level (TRL) for current AFC systems.

The Technical Readiness Level (TRL) of the discussed flow control systems is shown on Figure 25 above. Most of them are already conducting field tests (TRL 7) but not ready to be implemented safely into a real world scenario, a couple like flaps (rigid/ATEG/gurney) and vortex generators (AJVGs) are currently on TRL 9 and in commercialization. They are currently being offered as popular power-augmentation upgrades in the industry, so an analysis of their performance will also be taken into account in the case study.

Active AJVGs effectively delay stall and reduce fatigue issues up to a 25% and manage AEP increases of 5%, and since they are already being marketed they are a sensible choice to implement into our model. Although Gurney Flaps are a popular choice to support any flow control systems, in this thesis only the air jet vortex generator will be considered in the implementation to better focus our calculations and work within the results of already existing lift enhancing programs.

4.1.1 AJVG experiment

After the outsourcing of information to understand which active flow control solution may suit turbine blades the best, the decision was to try and implement Air Jet Vortex Generators as our flow separation control device. To understand the impact this system might have over an aerodynamic system an experiment [65] was conducted by N.A. Ahmed and S. Shun to study how the different aerodynamic coefficients might behave or how much of an improvement on the performance it might have.

To carry out the experiment a NACA 63-421 was equipped with 24 rectangular-shaped exponential nozzles spaced 30 mm between each other over the span of the wing. The orifices' longer dimension was orientated perpendicular to the cross-flow, which appears to produce stronger vortices [66], giving the nozzle a greater potential to maximize the use of energy being fed into it. Other studies prior to this experiment concluded that a skew of 60 degrees and a pitch angle of 30 degree produces good results under conditions of cyclical [7] and noncyclical changes in AOA [67], as well as other optimal configurations like placinng the AJVG arrays at chordwise locations of around 12.5% [68] which provides the greatest amount of clearance from internal pressure-tapping conduits built into the leading edge of the airfoil. All these configurations can be seen below on Figure 26 with a detailed schematic of the air supply.

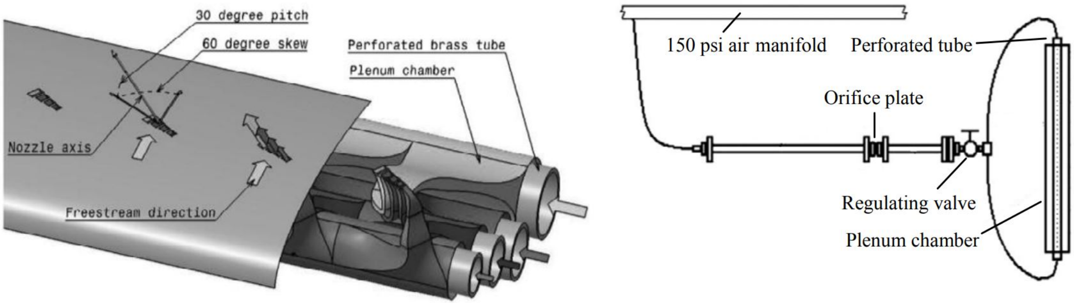

Figure 26: AJVG arrangement of the air supply. [65]

The airfoil was equipped with three rows of 48 static pressure taps each. These were connected to a multitube water manometer that measured pressure to then be integrated into the normal (c_n) and the tangential force coefficients (c_t). To measure the injection velocities (v_{jet}) from each of the four individual orifices making up the AJVG's (centerline and left-hand side) a Dantec hot wire system was used, with its readings being compensated for temperature and averaged to get the final velocity values.

To quantify the energy being consumed by an air jet the following Equation 2 of the momentum coef. c_M was used, taking into account the mass flow rate consumed by the jet ($\dot{m}_{jet}$), v_{jet}, dynamic pressure ($q = \frac{1}{2}\rho v_{\infty}^2$) and wing area (A):

$$C_\mu = (\dot{m}_{jet} v_{jet})/qA \tag{2}$$

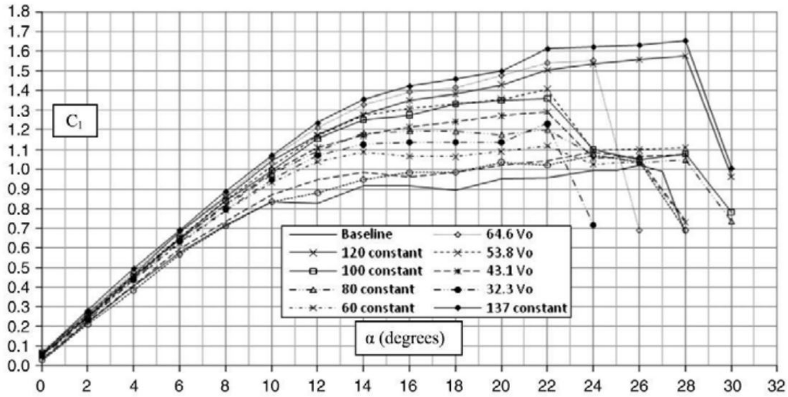

Figure 27: Lift coefficient (c_L) vs. angle of attack (AOA) [65]

In Figure 27 the lift coefficient (c_L) vs. AOA behaviour is plotted at different injection profiles, seeing positive results in an optimal range of AOA of 0-22 degrees. Figure 28 shows this increase in lift averaged over the aforementioned range of AOA when the baseline configuration is used (no jets), plotted against the energy consumption per jet.

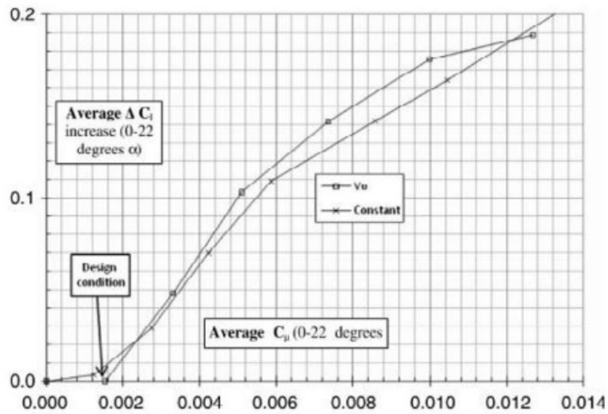

Figure 28: Average incremental c_L and c_μ (0-22 AOA) [65]

This experiment concluded that the biggest reduction in energy consumption happened at an average incremental gain in lift coefficient of 0.16. Something important to take into account is that the exponential velocity profile used around 14% less energy when compared with a constant velocity across the jet. The exponential jet seems to provide the greatest performance for a range of energy consumption beyond the design condition of the jet, which is something important in the case of the HAWT's and the difficulties discussed earlier.

With the experimental and theoretical background supporting AJVG's and their derivatives, especially exponential injection profiles that are proven to have less consumption, it can be confidently said that their use on full scale wind turbines can lead into bigger net gains in power output. Furthermore, it can solve the issues related to fatigue and noise generation that dynamic stall and other aerodynamic phenomena carry with them.

4.2 Building the script

After selecting an active flow control system with deep insight of their performance capabilities, an R script was developed to test the impact and the revenue model after implementing an AJVG array into real world wind turbines. This section will provide a comprehensive walk-through of the program with all the different variables explained and calculation details.

To begin with, the different market providers of this same technology are studied, since the TRL9 means that many different companies already provide similar technology to push AEP and increase total power extraction. For example, Siemens Gamesa already has a program set called Energy Thrust that promises an increase up to 5% in AEP using vortex generators, so by looking at their actual results we could get an understanding of were we stand regarding performance. We must take into account that our proposed active flow control system would include an AJVG array plus a couple of Gurney flaps, so the expected performance would be higher.

Type (MW)	**Country**	**Location**	**AEP increase (%)**
2,00	Spain	Lugo	2,61%
2,00	Portugal	Grande Lisboa	2,35%
0,85	Spain	La Rioja	0,93%
0,85	Spain	Burgos	3,14%
0,85	Spain	Pontevedra	5,29%
0,85	Ireland	Sligo	2,77%
0,85	China	Shandong	1,07%

Table 2: Sample of Siemens Gamesa Energy Thrust program database (see Annex B). [69]

Table 2 is a sample of a Siemens Gamesa Energy Thrust program database [69] consisting of the results of their AEP increase in many different wind turbines spread across Europe. This is essential to be able to study the expected results we might get when implementing these devices, and paired with all the bibliographical evidence the average AEP increase can be obtained for different types of turbines. To analyse it the different turbine types are separated into their most significant countries getting rid of outliers, resulting in Table 3 below.

Country	850 kW	2 MW
France	5,86%	2,16%
Italy	3,31%	1,85%
Portugal	-	1,98%
Spain	3,84%	2,17%

Table 3: Averages of % of AEP increase with Energy Thrust program.

As seen in the Table 3 above, this analysis resulted in an AEP increase of 4.156% in average for HAWT's of 850 kW and 2.6% for the 2 MW (2000 kW), roughly one third less than their smaller counterparts. To implement this into the model low power turbines will be considered as those under 1000 kW of installed power, using bigger AEP increase coefficients than the bigger than 1000 kW turbines. These will be the averages used to calculate the extra energy production our turbines will have with the system implemented. Giving this values some range in order to get estimations from favourable to more pessimistic scenarios, allowing an input from 1 to 10 in order to get optimistic (10) or pessimistic (1) results.

The total AEP is usually calculated as the installed power times the operation hours expected to be able to obtain the kWh that the generator can produce. Taking into account that the operation hours will be uneven most of the times and that not all the electricity generated can be marketed, a correction coefficient of 0.39 is applied as documented in a German market analysis of its wind turbine grid [70]. The 2 MW turbine we are going to use as an example would produce a total of 6800 MWh/yr, a value very similar to the orientative average shown in many wind turbine manufacturers' websites of 6000 MWh/yr.

Maintenance is a concurrent cost in wind turbines lifespans and the cost related to these activities can get as high as an 8% of the total revenue expected from the power generated [70] by them. The Air Jet Vortex Generators installed in the turbine blades would also need maintenance, an 8% of its energy production value as well, so as to ensure their proper functioning and apply preventive measures to minimize cost of corrective maintenance. This is also true when talking about the structural integrity of the blades, but fortunately avoiding stall derived fatigue issues and bending moments is possible with active flow control and these systems may provide as much as a 25% [62] reduction in maintenance costs. This profit greatly offsets the maintenance cost of the AJVG array, proving to be profitable the moment the system is equipped on the wind turbine.

As we are going to consider this analysis outside of the profitability and revenue systems of the wind turbine itself, the revenue generated each year by our system will finally be the difference between the total power generated and the AJVG power consumption, estimated to be a 10% of its total energy produced, all multiplied by the market cost of kWh at the desired moment of time. It is important to take into account that the AJVGs will have an exponential profile as in the previous section the geometry was proven to consume less power. As the example turbine we will study is set in Spain, the average cost of electricity in Spain in 2021 (0.2816 EUR/kWh) will be used to calculate the yearly profit after the AJVG implementation, taking into account its effects alone.

From an economic standpoint, the viability of installing an AJVG system directly depends on the investment cost at the beginning of the project, the price of components themselves. As not many companies share their production and installation costs some rough estimates are proposed for the study, but ultimately the model aims to study how this initial cost will affect the ROI and the years that must pass until the expenses are overcome and the model starts being profitable. Ultimately, the inputs that the script allows are: **x**, this total initial investment, as well as **pwr**, the installed power of the turbine and finally **y** from a scale of 1-10, which represents how optimistic we want the model to be.

```
profit(x,pwr,y)
```

The R function `profit` will return all the variables involved in the problem, as well as the ROI, years until profit and the yearly revenue distinguished between AEP increase and maintenance cost savings. Finally, it must be taken into account that most wind turbine farms are expected to be profitable under their lifespan, normally before 20 years after installation. If the total years before profit are greater than the aforementioned value, the script will inform that the model is not profitable.

4.3 Results discussion

In the following section a sample turbine will be analysed, and the results returned from the script will be discussed to be able to extract some conclusions. Further explanation about the functioning of the code and how to work with the variables in an R environment can be found in Annex A.

4.3.1 Economic impact

To get a greater understanding of how the different variables impact the system, two different wind turbines are selected among a big Spanish wind turbine database (Table 4), one of a higher installed power and dimensions and other of smaller size and less kilowatts. Table 5 sums up the specifications of the first turbine of the study: Siemens Gamesa $G80/2000$. As previously explained due to the power installed of this turbine the AEP increase ratio will be slightly lower, but the sheer amount of power its able to generate has the potential to end up being even more profitable than smaller counterparts like Acciona Energia's Bonus MK-IV, details on Table 6.

City	Name	Manufacturer	Turbine	Hub height (m)	N	AEP (kW)	Developer	Operator
Boal, Castropol	El Candal	Gamesa	G80/2000	67	19	38000	Producciones Energeticas Asturianas SL	#ND
Porto do Son,	Barbanza I	Made	AE-30	-	60	19800	Terranova	Acciona Energia
Valdoviño, Narón	Novo	Ecotecnia	48	-	25	18750	Energias Ambient. de Novo	Energias Ambient. de Novo
Mazaricos, Muros	Paxareiras I	Navantia-Siemens	Bonus Mk-IV	35	34	20400	Terranova/Acciona Energia	Eurus Energy
Muros, Carnota	Paxareiras II	Navantia-Siemens	Bonus Mk-IV	35	32	19200	Terranova/Acciona Energia	Eurus Energy
Camariñas	Pena Forcada	Navantia-Siemens	Izar 55/1300	-	26	33800	E.E. del Noroeste	E.E. del Noroeste
Abadín, Mondoñedo, Pastoriza	Farrapa	Gamesa	G80/2000	67	10	20000	Gamesa/Elawan	Gamesa
A Fonsagrada, Castroverde	Punago	Made	AE-46/I	-	46	30360	Acciona Energia	Acciona Energia
Rodeiro	Monte Cabezas	Ecotecnia	74	-	23	38410	Galicia Vento SL	Elecnor
Vilagarcía, Catoira	Xiabre I	Vestas	V90/1800	-	11	19800	Engasa	Engasa

Table 4: Sample of database with wind turbine specifications across Spain. [71]

Type	G80/2000
Manufacturer	Siemens Gamesa
Power (kW)	2000
Hub height (m)	67

Table 5: Sample 2MW turbine selected for study.

Type	Bonus Mk-IV
Manufacturer	Acciona Energía
Power (kW)	600
Hub height (m)	35

Table 6: Sample 600 kW turbine selected for study.

Something important to take into account is that the investment cost of the AJVG systems will be different between wind turbines with great differences in hub height, with bigger blade spans needing more jet injectors placed along the wing. This however would not follow a linear relationship since the main cost of this systems are not the actuators themselves but the installation of the whole grid and pneumatic network. For this particular study it has been considered that the cost of smaller wind turbines like the one shown in Table 6 is not less than 2/3 of the cost of implementing AJVGs on an average 65m of hub height multi-MW HAWT's have.

Taking all the above into account the first simulations where carried out with investment values (x) of 300k EUR for larger HAWT's, considering three different AEP increase scenarios to study which model might be the most profitable in many possible outcomes. This estimated value of initial investment places the total inital implementation cost of right under a million EUR, which seems reasonable when compared to the installation cost of large wind turbines like the one in study.

Below on Table 7 there is a summary of the economic impact of the implementation, with values like Return on Investment (ROI), a percentage between initial investment and annual profit; years before profit (YBP), the amount of years before overcoming the initial investment and net profit is achieved; annual revenue (AR), the yearly amount of money saved or generated and finally EEP (Extra Energy Profit), which is the amount relative to the AP which comes directly from the extra energy generated due to AFC system improving the turbine's AEP. A sample prompt generated at a request of a given scenario, installed power and investment cost would look like the following:

```
[1] "Expected return of investment in 6 year(s), with a ROI of
18%"

[2] "Annual savings of 167942 EUR, where 136656 EUR in regards to
maintenance and 45717 EUR of extra kWh generated."
```

	2000 kW	**600 kW**
ROI (%)	18	9
YBP	6	11
AR	167	55
EEP	46	21

Table 7: Comparison of implementation results between turbine types in neutral scenario (y=5).

The results above show that despite the lower investment in smaller turbines, multi-MW HAWT's benefit better from this active flow control add-on. In the 2MW turbine in study a ROI of 18% is expected, obtaining profit from the savings and power generated just 6 years after installation. The annual revenue expected from the use of this systems is a total of 167k EUR, from which 46k are due to the extra energy obtained from the AEP increase AFC systems provide. Rest of the profit comes from savings in maintenance costs, 136k EUR in the case of the larger turbine. This impact is the most significant as the results start right from the beginning, lowering fatigue issues by avoiding stall as often and indirectly enlarging their lifespan before the need for corrective maintenance. As most of the savings come from the reduction in maintenance costs derived from fatigue avoidance, an issue with a common root cause is noise pollution reduction product of AFC systems. In our case AJVG's also require a lot of maintenance that must be taken into account just as the whole turbine system's maintenance, but with the benefit of a reduced energy consumption due to the use of exponential injection profiles.

Below Table 8 groups all the values resulting from various simulations with different scenarios relative to the expectations of the AJVG performance (x).

	2000 kW (x=300k)				**600 kW (x=200k)**			
Scenario type (y)	**ROI (%)**	**YBP**	**AR**	**EEP**	**ROI (%)**	**YBP**	**AR**	**EEP**
Pessimistic (0)	15	7	144	11	7	14	45	5
Neutral (5)	18	6	167	46	9	11	55	21
Optimistic (10)	21	5	195	86	11	9	68	39

Table 8: Economic impact of implementation in 3 different scenarios (k€).

As a rule of thumb, an investment stops being worth it when its ROI is less than 7%, like in the pessimistic scenario of implementation in low installed power turbine, thus deeming it not a sensible business decision. On top of this as previously explained, wind turbine farms are usually projected to have profit in their average 20 years of lifespan. Both this constraints where considered in the simulator, with the script returning a prompt like the following when ROI exceeds the bottom 7% margin or the years before profit are higher than 19.

```
[1] "Investment not worth it."
```

The usefulness of the tool built in the script shines here at obtaining a ceiling value for the initial AFC system implemented where the economic impact is profitable and understand at a broad level how the different variables may behave.

	2000 kW	**600 kW**
ROI cap (k€)	750	200
YBP cap (k€)	1000	350

Table 9: Ceiling values of investment per blade of different turbine types (k€).

The values on Table 9 above correspond to the implementation costs of AJVG systems on one singular blade so, as explained in the section before, to consider the cost of the whole HAWT this value has to be multiplied by 3. This way, in a neutral scenario the maximum implementation cost for multi-MW turbines would be 2.25 million EUR per HAWT, and 200k EUR for their smaller installed power counterparts. These are the values business developers have to take into account and try to shoot at lower initial price investments to make the implementation of this systems a profitable economic decision.

After the case study performed above over two different types of turbines, it can easily seen than despite their larger investment costs and lower AEP increase when using AJVG arrays mounted on the enormus blades, it is more profitable to do so on bigger HAWT's. The lower AEP is offset by their bigger installed power, allowing for great energy production increases despite their low relative increment. However, this advantage is due to their bigger spans and they experience the most adverse and off-design conditions, thus benefiting more of the stall-avoidance capabilities, drag reduction and delay of boundary layer separation.

As an example, turbine G80/2000 shown above on Table 5 would produce a total revenue of 167k EUR after overcoming the initial investment of 0.9M EUR over the first six years, see Table 7. Applying AFC control to every one of the 19 turbines on the sample windfarm in Boal, Castropol, in a neutral scenario would mean an initial investment of 17 million EUR but a yearly revenue of 3 million EUR after the return on investment.

A summary of the values used as in the sample case study of the Siemens Gamesa G80/2000 horizontal wind turbine are collected below in Table 10, as well as the results returned by the script.

Variable	Units	Value	Ref.
x	EUR	300000	-
pwr	kW	2000	-
y	-	5	-
ecost	EUR	0.2816	-
use	-	0.39	-
mantred	-	0.25	-
mant	-	0.08	-
exAEP	kW	180385.9	-
expred	-	0,86	-
n	years	6	-
ROI	%	18	-
year	EUR	167942	-
mant2	EUR	136656	-
revenue	EUR	45717	-

Table 10: Input variables and results from case study.

4.3.2 Environmental impact

As previously explained, noise pollution is a great concern nowadays that the demand for wind energy extraction is in the rise and more wind farms are installed near population, in the vicinity of human habitats where noise, vibrations and plain visual impact have been reported by locals. Among all the concerns one of the major offenders is aerodynamic derived wind turbine noise, not only as an environmental threat but to the whole wind power industry as a whole.

Research focused on the link between wind turbine noise and potential implications on mental and physical health [72] demonstrated that there is a correlation between decibel levels and annoyance/sleep disturbance. Interestingly enough, the particular sound of wind turbines turned out to be perceived as more annoying than other noise sources at the same Sound Pressure Level (SPL) [73], specially in rural areas where less noise pollution is expected and the impact on sleep and mental health is more severe. Figure 29 below demonstrates the percentage of annoyance relative to sound pressure of different noise sources, and as it can be seen wind turbines seem to upset citizens before reaching higher values where other transportation means lie.

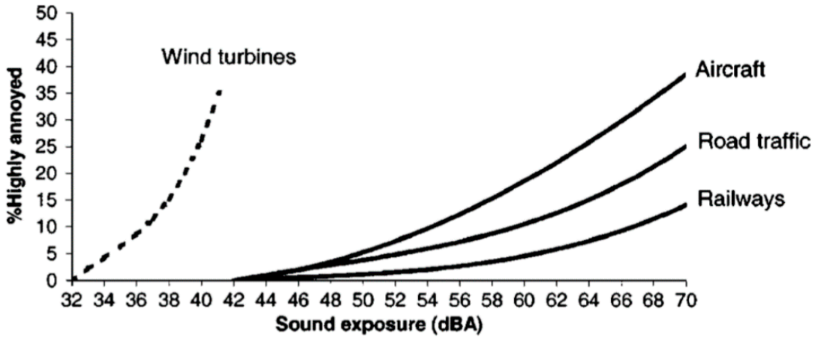

Figure 29: Comparison between annoyance levels and perception of wind turbine noise and transportation. [74]

The application of active flow control methods that improve aerodynamic behaviour of the wind turbine allow for a noise generation reduction targeting different noise sources derived from aeroacoustic phenomena. In this case study, applying the bibliographic decibel reduction value of Air Jet Vortex Generators of 3.5 dB due to stall avoidance and boundary layer separation delay returns a reduction of 25% of afflicted population as seen in Figure 29 above.

Further research has to be conducted to test the noise produced by the active flow control system itself, the air jets and holes drilled in the blade are noise generators as previously discussed and should be taken into account accordingly. Other structural or mechanical noise sources can be dampened with the use of other cost effective measures, and further research into the structural vibration noise reduction that stall avoidance allows may show that flow control could hinder noise complaints about wind power extraction obsolete.

The economical benefits alone have an implicit environmental impact by lowering the cost of energy (COE) and thus making wind turbines more viable as a power generation system than other fossil fuel counterparts. On December 2019, the European Council passed a proposal that aimed at making Europe climate neutral by the year 2030, meaning the greenhouse gases will be emitted at the same rate as they are being removed from the atmosphere [75]. Lowering our dependence on fossil fuel energy power extraction and supporting renewable energy sources means that COE must lower for it to be viable in the capitalist driven world we live in. Ultimately, implementation of active flow control in wind turbines effectively helps towards transitioning toward a more environmental responsible society.

5 Conclusions

Each year the desire to harvest more energy from the wind brings an enlargement in wind turbine sizes, in their rotor diameter and their blade spans. Working towards a more sustainable future requires to first overcome the challenges wind turbines face like rapid wind direction and velocity changes, among others. The product of these phenomena are aerodynamic related issues that lead to fatigue, noise generation and overall less power extraction.

Many active flow solutions work towards the reduction of the previous effects by means of variable geometry, advancing/delaying transition and utilizing turbulence to offset the negative effects inherent to the scale of these blades. Exponential AJVGs effectively delay stall and reduce fatigue issues up to a 25% and manage AEP increases of 5% with an energy consumption reduction of 14%, and since they are already being marketed they are a sensible choice to implement into our case study.

The model developed for testing the implementation of an AJVG array of an initial investment cost of under a million euro for a single 2MW horizontal wind turbine returned a yearly revenue of 167k EUR starting to make profit after overcoming the initial investment and derived O&M consts in 6 years, with a return on investment of 18%. An 80% of the revenue comes as corrective maintenance savings thanks to the fatigue reduction and load alleviation AJVG systems provide. The other 20% is related from the marketed extra energy produced product of the AEP increase of up to 5% in bigger MW-turbines. The environmental impact resulting of the implementation of this technology is evident, achieving a 25% reduction of afflicted population due to noise pollution thanks to an average sound pressure dampening of 3.5 dB. Not only that, but thanks to the potential increased profitability of the wind turbine technology and with the decrease of COE implementing flow control systems directly helps the building of a climate neutral world.

Some further research can be done to improve both AEP increase and structural integrity improvement but issues like noise generation and cost have to be taken into account as well in order to make a sensible economic decision and carry on with the implementation. The script presented above can be used to test the aforementioned possibilities and study at a broad level how an implementation as such can evolve over the years.

Finally, possible future steps to be done after this project include, but are not limited to: possibility to add Gurney Flaps to the AJVG arrays to increase AEP and noise reduction, as Gurney Flaps are an inexpensive addition to any blade that reports many benefits, but the exact variables in play must be researched. Market price of kWh is highly volatile and does not stagnate at a fixed value like in the model, so a prediction of the price trend over the year span in study is advised to get better results. Finally, the use of R coding language and its `data.table` package allow for this model to be run as a function over large databases (DDBB) and broadly observe the impact over a large number of HAWTs/wind farms. To do so, a statement like the following can be implemented over large DDBB using the variables inside them (eg. pwr is a column insde the DDBB with a value for each WT):

```
DDBB['selection',profit:=profit(x,pwr,etc.)]
```

All in all, the case study developed after the bibliographic study and building the script returned sensible results with well documented variables, using as an initial target variable the initial system cost. The model can function as an orientative tool to further understand the possibilities and constraints of the implementation of active flow control technology, specifically Air Jet Vortex Generator arrays, in multi-MW horizontal axis wind turbines.

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