



Optimizing Vortex Generator Configurations on Commercial Aircraft Lucas Hong

Abstract

This paper discusses the optimal size and geometry of generators on commercial aircraft to prevent stalling while minimizing drag generated by the vortex generators (VG) based on literature review. While VGs equipment is necessary for the airplane's safety, they inevitably increase skin friction drag on the wing. Although it increases the safety of the aircraft, this added turbulence increases drag and fuel consumption, which increases the budget, especially over long-term operation. This paper will review the results of multiple published research papers, and determine the best outcome by combining the findings throughout different papers. The goal of this paper is to find a VG that can maximize passenger safety by delaying flow separation while minimizing the economic and aerodynamic costs of excess drag. By analyzing numerous aerodynamic principles, this paper investigates how the orientation, height, and geometry of VGs can be optimized and how these devices ensure every passenger's safety without sacrificing fuel economy. Using the data from the paper, the literature reviewed concluded that the optimization of a vortex generator likely have a Trapezoidal shape counter-rotating VG, height of $0.8-1.0\delta$, 10-18 degrees of incidence angle, placed at 20% of chord wing/separation region, 2.5h spacing within each pair and 7-8h between each pair of VG. (δ =boundary layer thickness; h=height of VG).

Introduction

Aerodynamics is a critical part of engineering, covering a massive aspect of modern human life. Over the past century, humans have been relentlessly working to create the perfect structure to maximize aerodynamic efficiency, yet there is no single perfect answer to the question. Every aircraft design is a compromise between safety, speed, and efficiency. Specifically, drag is one of the largest issues regarding aerodynamic principles experienced by aircraft; and airflow separation is one of the factors that causes the majority of the drag to form. As air travels over the surface of an object, it eventually loses momentum and separates from the surface, leading to loss of lift and creation of a massive drag. To address this issue, engineers add vortex generators on the surface of the wing to intentionally generate turbulence flow, which allows the boundary layer to stay attached to the wing at greater angles of attack. As air flows over the surface of an aircraft's wing, not all air particles experience the same velocity [1]. Due to the air's viscosity, the air molecules that are in physical contact with the wing are at a complete stop, which is known as the "no-slip condition" [2]. The air above this stationary layer moves increasingly faster until the flow reaches the velocity of the "free-stream" air. This thin region of air is known as the boundary layer [1].

A similar concept of vortex generators used outside of air travel is the dimples on a golf ball. By creating dimples on a golf ball, it stabilizes the ball's flight as well as decreases its drag coefficient [3]. This is due to the form drag created after the flow separates at the separation point. Form drag, also known as pressure drag, occurs when flow separation creates a low-pressure wake behind the object, creating a pressure difference between the front and rear of the object [4]. It is similar to how lift is created; but instead of the pressure difference between the top and bottom of the object, it is the difference from the front and the back [3]. Vortex Generators (VGs) delay flow separation point by creating a turbulent flow which stays on the

object and leads to a smaller area of pressure difference, thus reducing the drag. However, dimples provide limited benefit on commercial aircraft because aircraft generally encounter highly turbulent wind at high Reynolds numbers. Reynolds number is defined as a value used to predict flow patterns an object is encountering [1]. Higher Reynolds numbers generally means a more turbulent flow, while a smaller value represents a laminar flow [1]. Turbulent flow represents chaotic flow that crosses paths and creates more drag; in contrast, laminar flow is smooth, predictable airflow that moves in layers. Reynolds number is calculated by dividing the fluid's density, velocity, and the object's dimensions by viscosity of the fluid. Therefore, as the length and velocity increase, Reynolds number generally increases. A golf ball travelling at 150 MPH has a Reynolds number of approximately 1.94×10^5 . This is where the dimple shows its advantages over smooth surfaces and results in a lower drag coefficient. On the other hand, because of the larger size of an airplane, the turbulent flow created by dimples disturbed the aerodynamics of the airplane rather than improved it. For example, the Reynolds number for a Boeing 737 travelling at 500 MPH has the Reynolds number of approximately 2.34×10^7 . Therefore, the dimples would only work well when an object is experiencing laminar and stable flow, but it would worsen the aerodynamic of the object if it is met with more turbulent flow, which is what commercial aircraft have to face for the majority of the time.

$$\text{Reynold number's formula} = Re = \frac{\rho \cdot u \cdot L}{\mu}, \text{ where}$$

ρ is the density of the fluid (SI units: kg/m³)

u is the flow velocity (m/s)

L is a characteristic length (m)

μ is the dynamic viscosity of the fluid (Pa·s or N·s/m² or kg/(m·s))

The main way that researchers and engineers optimize new designs is by running computational-aided models and using mathematical equations in order to optimize the arrangement as precisely as possible. Therefore, this paper will reference multiple research studies, and by evaluating these computational models, we can determine aerodynamic trends that lead to the optimized VG.

Background

1. How do Wings Produce Lift and the Threat of Flow Separation

In order to understand why vortex generators are essential for modern aircraft, we must first understand how wings produce lift. Lift is mainly produced by pressure difference (Bernoulli's Principle) and action-reaction force (Newton's Third Law) [1]. Firstly, when the airfoil splits the air into top and bottom, the air moving over the curved top surface speeds up, which decreases the pressure above the wing. On the other hand, the air moving underneath the wing slows down, resulting in higher pressure. This pressure difference pushes the wing upward, resulting in lift, and this is known as Bernoulli's Principle. Secondly, according to Newton's Third Principle, as the airfoil directs the air downwards, it results in a corresponding upward force on the airfoil, which also generates lift. However, as the air moves toward the trailing edge of the wing, it results in an adverse pressure gradient [1], which happens when the air moves uphill and against the flow direction, resulting in the boundary layer detaching from the wing, which can cause what is known as flow separation. When flow separation occurs, it significantly affects

a wing's ability to generate lift as well as increases its drag coefficient [4]. Moreover, it creates a turbulent wake behind the wing, resulting in a massive pressure imbalance between the front and back of the object. This is known as "form drag" (also known as pressure drag).

2. How a Stall Happens

A stall is a dangerous aerodynamic condition that occurs when the airflow separates from the wing [1], resulting in a sudden loss of lift and causing the plane to descend uncontrollably. There are two common scenarios when a stall is likely to happen. First is when the plane does not carry enough speed, so the air does not have enough kinetic energy to stay attached to the wing. Second is when the plane has too high of Angle of Attack (AoA), making the air unable to make the sharp turn over the top of the wing, causing immediate separation.

The Angle of Attack is the angle between an aircraft wing's chord line (leading-to-trailing edge) and the oncoming air. The angle determines how rapidly a plane can climb up, which is crucial for initial take-off or in any emergency where a plane has to rapidly increase in altitude. As the AoA increases, the wing produces more lift, but it is harder for the air to go over the top of the wing since the airflow must go through a sharper change in direction and results in a greater pressure difference. As the angle of attack keeps increasing, the air is unable to flow through the top part of the airfoil smoothly, and air starts to detach from the wing. When the plane reaches the Critical Angle of Attack (usually around 15-20°) [1], the boundary layer completely runs out of energy. The air no longer stays attached to the airfoil, and the airflow separates from the surface of the wing. This results in the sudden loss of lift, making the airplane stall and fall under gravity's control. Though it is possible to save the airplane by increasing speed and reducing the angle of attack, past incidents constantly remind us of the danger of a stall.

3. How Vortex Generators Work

Vortex generators are implemented specifically to prevent airflow separation by reenergizing the boundary layer. These devices consist of small, delta/trapezoid shaped fins placed near the flow separation point, normally between 10% and 20% of the wing chord [5]. Engineers designed their size to be just tall enough to go through the boundary layer and pierce the free-stream air. Moreover, they are installed at a specific angle relative to the airflow.

When the high-velocity air meets the angled fin, a region of high pressure forms on the windward (front) side, while a low-pressure zone forms on the leeward (back) side. Because fluids naturally flow from high pressure to low pressure, the air is forced towards the backside of the airfoil, which forces the air to stay attached to the airfoil. In addition, this action forces the air to roll up into an energetic vortex, which further helps it to trail downstream along the surface of the wing. These vortices rotate to draw fast moving air from the free stream and sweep it downward, pushing it towards the slowest parts of the boundary layer. [6] Thus, the slower air particles are reenergized and increase in speed, allowing the slow moving air to gain energy in order to push through the adverse pressure gradient. As a result, the airflow stays on the airfoil for a longer distance and therefore delaying airflow separation to maintain lift and high angle of attack. However, VGs increase turbulence and surface area, which increases skin friction drag. As drag increases, the plane becomes less fuel efficient. Therefore, optimizing VG orientation, height, and geometry is crucial to find the configuration that increases safety while keeping the drag low.

4. Induced Drag and other aspects

Other than vortex generators, there are numerous other aerodynamic phenomena that affect how a wing behaves. For example, another major drag that airfoil encounters is induced drag. Because fluids flow from high to low pressure regions, the high-pressure air beneath the wing will attempt to move to the low-pressure region. Consequently, it curls outward and escapes around the ends of the wings. This flow creates a powerful vortex at each wingtip [1], and these wingtip vortices form a massive, continuous vortex known as a trailing vortex.

The creation of these wingtip vortices comes with significant downside for drag coefficient. As the vortices spin, they drag the surrounding air downward, creating a flow behind the trailing edge of the wing, which is known as downwash. Because lift is always perpendicular to the relative wind, the downward angle of the downwash forces the aircraft's total lift vector to tilt backward and upwards. This component of the lift force acts as drag, and this specific form of drag is defined as induced drag. It is an inevitable byproduct of generating lift; therefore, it is impossible to completely eliminate induced drag. Lastly, induced drag is most severe when the aircraft is flying slowly and at a high angle of attack, which also when vortex generators provide the greatest benefit.

In order to reduce the effect of induced drag, engineers use two main designs: maximizing the aspect ratio and installing winglets. Aspect ratio is the ratio of a wing's span and its chord (its width). Aircraft designed with a high aspect ratio often have longer wings, and this allows the wingtip vortices to be further away from the wing's lifting surface, which decreases the strength of the downwash. However, an overly long wingspan is impractical as it can create structural challenges, especially in turbulent conditions. Moreover, it is impractical as some airports' gates are not designed for such a long wingspan. Therefore, engineers install winglets: a vertical or sharply angled extension mounted directly at the wingtips. Winglets serve as physical barriers that stop the high-pressure air from easily curling over the wingtip. By disrupting this flow, winglets significantly weaken the formation of the trailing vortices, reducing downwash and decreasing induced drag. Therefore, by combining high aspect ratios, winglets and vortex generators, companies were able to create safe and efficient modern aircraft.

Methodology

In the paper Optimisation of Vortex Generators for Stall Speed Reduction [5], the vortex generators have eight variables. They include VG type, height, length, orientation, thickness, spacing between VG pairs relative to the height, spacing between the different parts of a VG pair relative to the multiple of the device height, and chordwise VG position [2]. Furthermore, in order to simplify the experiment, the optimisation was set to one airfoil and the objective became to improve lift at the original stall speed and at a high angle of attack with fully extended flaps of a Cessna 208. The initial study for the inboard section was performed at a $Re = 3.1 \cdot 10^6$, the free stream velocity was set to 113 km/h (stall speed) and the flap was fully extended. The researchers used ANSYS FLUENT Meshing which allowed them to define the experimental values in different regions.

The second research paper Design Optimization of Vortex Generator Array to Delay Pitch-up on Tailless Aircraft investigates how vortex generator arrays can be optimized to delay pitch-up and

improve stability on tailless aircraft configurations. Similar to the first group of researchers, Lee et al [6] decided to use a mathematical model to simulate the best configuration for the VG. The paper separates the factors into four different cases, which are Changing Chordwise Position of VG Array, Changing Incidence Angle of VGs, Changing Space between VGs, and Changing Size of VGs. Firstly, the researchers determined the baseline VG position by running several simulations and placed it near the separated flow region. After finding out the results, the researchers used diagrams and graphs for showing the results of every position tested in the experiment in relation to the Pitching moment coefficient. Pitching moment coefficient is a dimensionless parameter that quantifies the pitching moment (nose-up or nose-down) acting on an airfoil or aircraft. A positive coefficient implies a nose-up moment, while negative implies nose-down. It is calculated by the following equation: $C_M = \frac{M}{q \cdot S \cdot c}$, where M = pitching moment, q = pressure of the air, S = wing area, and c = mean chord. The researchers used this to determine the effectiveness of the VG on various designs.

Because of real-time factors that CFD cannot simulate, actual wind tunnel experimental data is also necessary for real world optimization. Therefore, in the paper “Control of a decelerating boundary layer. Part 1: Optimization of passive vortex generators” by Godard and Stanislas, they use a device called AEROMEMS — microscopic sensors built onto surfaces to measure airflow — to gain data from a wind tunnel experiment. Furthermore, instead of building a 3D airfoil, they simplified it to a 2D model. They also used equipment such as hot-film shear stress probes and Particle Image Velocimetry in order to map the data points and track the data [7]. Lastly, Lin review compared the difference of traditional VG that grows above the boundary layer and low-profile VG, and found that low-profile VG are more effective at reenergizing the air while not generating excess drag [8].

Results

Based on the mathematical model, the researchers successfully determined the optimal orientation of the VG while limiting factors such as flaps, purpose of the VG, and limiting design parameters to simplify the experimental configuration. According to the study, the application of low-profile VG can reduce up to 38% of drag when used at lift coefficient 0.572 [5]. However, for high lift configurations, the risk for flow separation at low angles of attack can pose a serious risk to lift generation. To address this issue, researchers suggest utilizing low-profile VG in the downstream of the flap’s leading edge in order to maintain the attached flow at lower angle of attack. In addition to reducing drag, low-profile VGs also delay flow separation at high angles of attack and improve airflow attachment. The researchers determined that VG heights between 0.8δ and 1.0δ have the best balance between airflow energization and drag reduction [5]. Heights greater than the local boundary layer generated stronger vortices, but also created excessive drag that reduced the aircraft’s efficiency. Low-profile VG can often provide benefits since they have significantly less drag compared to full sized VG. A low-profile VG is a Vortex Generator that sits at or slightly short of the local boundary layer thickness instead of being oversized like traditional configurations. By staying in the boundary layer, the VG avoids disturbing the fast-moving free-stream air. This means that it does not generate excess form drag, while still being able to restore momentum to the slower boundary layer to delay flow separation. Furthermore, the optimal VG spacing of around $2.5h$ identified in this experiment also matches the optimum found in other studies. All the data provided are in variable δ

(boundary layer thickness) or h (height of VG). This is because every airplane has a different size, and the effectiveness of VG depends greatly on the sizing of the airplane. Therefore, the optimization shouldn't be a single number; rather, it should be a set of values based on boundary-layer thickness and vortex-generator height [5,7,8]. General Boundary layer formula is shown as the following.

$$\text{Laminar boundary layer thickness} = \delta(x) = 5.0 \sqrt{\frac{\nu x}{u_0}}$$

$$\text{Turbulent boundary layer thickness} = (\delta(x) = 0.37 \frac{x}{Re^{1/5}}$$

u_0 = freestream velocity

x = distance downstream from the start of boundary layer

ν = kinematic viscosity

Re = Reynold's number

Parameter	Meyer et al. [5]	Lee et al. [6]	Lin Review [7]	Godard & Stanislas [8]
VG shape	Counter-rotating trapezoidal vane	Rectangular vane model	Counter-rotating Vanes	Low-profile rectangular vane
Height (δ : thickness of boundary layer)	0.5 δ – 1.8 δ	Low-profile VG	0.1 δ –0.5 δ	0.2 δ –0.5 δ
Length (fixed) (h = height)	4 h	4 h	2.5–4 h	5 h
Thickness (fixed, mm)	0.5mm	As thin as possible	As thin as possible	N/A
Incidence/Orientation Angle	18°	10°	15°–23°	10°–16°
Spacing between VG pairs	4.5 h - 10 h	5-8 h	6 h –10 h	6 h –8 h
Spacing within a VG pair	1 h - 2.5 h	1 h -4 h	1 h –3 h	2 h –4 h
Chordwise position (fixed)	20% chord main wing	Near separated point	10 h -30 h upstream of separation line	Near separation point

Table 1: Compiled Literature Values from different paper

Lee et al [6] individually graphed and showed the difference between the pitching moment coefficient in each and every individual case. Pitching moment coefficient is a dimensionless parameter that quantifies the pitching moment (nose-up or nose-down) acting on

an airfoil or aircraft. A positive coefficient implies a nose-up moment, while negative implies nose-down. It is calculated by the following equation: $C_M = \frac{M}{qSc}$, where M = pitching moment, q = pressure, S = wing area, and c = mean chord. The researchers used this to determine the effectiveness of the VG on various designs. From the first case, the experimental data shows that the pitching movement coefficient is the most negative when the VG are the closest to the wing, proving that it is best to reenergize the slower moving air when they are closer to the leading edge of the airfoil.

For case two, the researchers changed the incidence angle of the VGs on the airfoil. They varied the angle from -20 to 20 degrees, and determined the absolute best configuration to be a 10-degree angle facing into the oncoming airflow. Angles shallower than 10 degrees failed to efficiently force the air to energize the slower moving air vortex, failing to stay attached to the boundary layer to the wing to prevent stalling. On the other hand, angles steeper than 10 degrees caused the VGs to act like airbrakes. At steeper angles, they generate excessive drag and break the vortices into turbulence. Therefore, the 10-degree orientation is the perfect balance which creates an organized vortex while minimizing the aircraft's overall drag coefficient. Additionally, Lee et al. also discovered that when the incidence angles exceed 14°, the vortices become unstable and break into turbulence. Therefore, the optimal incidence angle is a balance between vortex strength and drag. From all the data derived from multiple published research papers [5,6,7,8], we can finalize a table that is more universal and can be adapted to modern commercial aircraft.

Parameter	Literature conclusion
Shape	Trapezoidal
Height	0.8δ
Length	4h–5h
Thickness	0.05h
Incidence Angle	10°–18°
Pair Spacing	2.5h–3h
Array Spacing	7h–8h
Chordwise Position	20% chord or immediately before separation
Configuration	Counter-rotating pairs

Table 2: Finalized parameter of VG optimization

Discussion

In addition to the data we have obtained from references [5,6,7,8], there are a few other improvements that would result in better optimization. A trend that is not experimented by the

researchers is a variable dimension vortex generator. Because of factors such as boundary layer thickness, Reynolds number and sweep angle, a variable VG geometry might be more optimal than a uniform dimension. For example, because airfoils are swept backwards, the incidence angle should be greater at the root of the airfoil, and decrease the angle as it grows out towards the tip. This would maximize the ability to face oncoming airflow at the most effective angle. Secondly, the height should also be adaptive. From the data, the height should be around 0.8 times the boundary layer [5]. However, the height of the boundary layer varies throughout the airfoil. Therefore, the height of VG would likely be higher near the root of the aircraft and decrease in size as it goes towards the tip.

If there is another experiment conducted to further optimize VG, there should be a few more aspects to be experimented. Firstly, the shape of the VG still has room for further investigation. It is commonly known that Delta wings are more aggressive [8], which means that they are effective at drawing more air to energize the boundary layer, but this comes at the cost. Although the most common type of VG is trapezoid/delta shaped, possibilities such as a Double Row Vortex Generator are less commonly investigated. However, companies might not consider these configurations due to difficulties in manufacturing. Secondly, future studies could utilize Deep Reinforcement Learning, which is a branch of artificial intelligence that could optimize principles by pattern recognition. Therefore, AI algorithms can possibly create chaotic and asymmetrical patterns that humans would not have thought of. Thirdly, more researchers are being done upon different approaches to traditional VG. For example, Boeing has been developing a technology called SMART Vortex generator [9]. SMART stands for “shape memory alloy reconfigurable technology”. Using this technology, the vortex generator can retract when the temperature is low, which occurs at cruising conditions, and extend back as the temperature increases. However, planes operating in extreme cold conditions can lead to false deployment of VG; therefore, the researchers are working on another version where pilots can manually control them, such as Morphing Vortex Generators. They are VG that can retract into the fuselage/wing of the aircraft when the airplane is in a stable flight condition. Therefore, the airfoil can be flat while cruising and deploy back during takeoff/landing, similar to flaps. Another similar concept but a completely different approach is Synthetic Jet Actuators. These devices utilize a stream of compressed air to generate vortices, creating the same effect of vortex generators without the penalties of drag.

Limitations

There are certainly limitations preventing us from creating the optimal configuration of VGs that is applicable to all aircraft. For example, although the computational-aided models and mathematics equations provide valuable data for vortex generator optimization, CFD simulations nevertheless may not perfectly match real-world scenarios and behavior. Errors can occur from changes in mesh resolution, models, or atmospheric assumptions. These can significantly affect the outcome of different experiments. Furthermore, these results were under specific circumstances, including fixed Reynolds numbers, flap configurations, and aircraft geometries. The study conducted by Meyer et al. focused on a Cessna 208 configuration, while Lee et al. base their CFD model on a lambda wing aircraft. Furthermore, although Lin review gave us insights of multiple different experiments and results in a more universal data set, the paper focuses exclusively on low profile VG of 0.1- 0.5 δ . As a result, the optimal VG dimensions and orientations in these studies may not directly transfer to all commercial aircraft. However, these

results still allow us to gain an insight of the range of optimal VG, and explore the aerodynamic reasoning behind the optimization.

Conclusion

In conclusion, the optimization of vortex generators (VGs) on commercial aircraft is a compromise between maximizing aerodynamic safety and minimizing economic drag penalties. By combining the data from Meyer et al., Lee et al., Godard and Stanislas, and Lin, several common optimization trends emerge [5,6,7,8]. Firstly, the implementation of low-profile VGs are proven to be one of the most efficient configurations in terms of size. By scaling the height of the VG to precisely match the thickness of the boundary layer, the VG successfully transfers high-momentum free-stream air into the slower moving air particles near the surface of the airfoil. Secondly, the computational models determine that VGs are most effective when placed near the leading edge of the separated flow region. This allows them to reenergize the air before the adverse pressure gradient becomes too great. Furthermore, in order to prevent vortex interference, which is when the adjacent vortex interrupts each other and loses kinetic energy, the ideal spacing within each VG pair should be 2.5 times the height of the VG. Finally, the angle of incidence should be between 10 and 18 degrees to generate the best energetic vortex that sweeps the boundary layer efficiently.

Although it is nearly impossible to find the absolute best configuration because of different uncontrollable conditions such as crosswind, temperature, rain and other natural factors, through the use of computational modeling, we can predict and minimize the drag penalties of safety equipment such as VGs by balancing effectiveness with drag penalty. By utilizing precisely spaced, low-profile vortex generator arrays, it ensures the maximum margin of safety while maintaining the strict fuel efficiency required for commercial air travel. Furthermore, the concepts of optimizing VG are not limited to commercial aviation. These concepts can also be applied to unmanned aerial vehicles (UAVs), wind turbines, automobiles, and future high-efficiency transportation systems; therefore, this paper contributes to designing safer, more fuel-efficient, and more stable aircraft for future transportation systems.

Beyond identifying optimal vortex generator dimensions, this study contributes to the aerospace community by synthesizing optimization trends from multiple independent investigations into a unified design framework. Rather than focusing on a single aircraft configuration, the paper identifies common aerodynamic principles that remain consistent across different airfoils, Reynolds numbers, and mission profiles. These findings may help guide preliminary vortex generator design for future commercial aircraft, unmanned aerial vehicles, and other aerodynamic systems before more detailed computational or experimental analysis is performed. Furthermore, the proposed concept of adaptive vortex generator arrays, where VG height and incidence angle vary according to local boundary-layer conditions, provides a potential direction for future aerodynamic research and may contribute to the development of more fuel-efficient and environmentally sustainable aircraft.

References

- [1] Anderson, J. D. (2017). Fundamentals of aerodynamics (6th ed.). McGraw-Hill Education.
- [2] Benson, T. (2021, May 13). Boundary layer. NASA Glenn Research Center.
<https://www.grc.nasa.gov/www/k-12/BGP/boundlay.html>
- [3] Hall, N. (2023, September 11). Drag of a sphere. NASA Glenn Research Center.
<https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/drag-of-a-sphere/>
- [4] SKYbrary. (2021, May 25). Form drag. SKYbrary Aviation Safety.
<https://skybrary.aero/articles/form-drag>
- [5] Meyer, J., Okfen, P., & Bil, C. (2020). Optimisation of vortex generators for stall speed reduction. Proceedings of the International Council of the Aeronautical Sciences (ICAS 2020).
https://www.icas.org/ICAS_ARCHIVE/ICAS2020/data/papers/ICAS2020_0311_paper.pdf
- [6] Lee, S., & Kim, C. (2018). Design optimization of vortex generator array to delay pitch-up on tailless aircraft. Proceedings of the 10th International Conference on Computational Fluid Dynamics (ICCFD10). <https://www.iccfd.org/iccfd10/papers/ICCFD10-019-Paper.pdf>
- [7] Godard, G., & Stanislas, M. (2006). Control of a decelerating boundary layer. Part 1: Optimization of passive vortex generators. Aerospace Science and Technology, 10(3), 181–191.
<https://doi.org/10.1016/j.ast.2005.11.007>
- [8] Lin, J. C. (2002). Review of research on low-profile vortex generators to control boundary-layer separation. Progress in Aerospace Sciences, 38(4–5), 389–420.
[https://doi.org/10.1016/S0376-0421\(02\)00010-6](https://doi.org/10.1016/S0376-0421(02)00010-6)
- [9] Boeing. (2022). Shape-shifting: The future of sustainable flight gets SMART. Boeing.
<https://www.boeing.com/company/about-bca/washington/shape-shifting>