

COB-2023-0371

REVIEW OF THE TRANSITION PHENOMENA OVER SWEEPED WINGS

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Abstract. *The drag force is ultimately linked to the aircraft performance, as it is inherited from the interaction between the airflow and the body. For conventional and commercial airplanes, although the wing is an aerodynamic device due to its usually low drag coefficient, if it is compared to other kinds of bodies, it is responsible for a huge portion of the airplane total drag. Since the drag is an effort that opposes the aircraft movement, it will impact the net thrust and the fuel consumption. Thus, it is of utmost desire for researchers and aircraft developers to decrease this aerodynamic force. However, working with the wing shape to reduce its drag has its limitations and other alternatives have been studied in the last years to reduce the drag via passive or active boundary layer control. The boundary layer, depending on the flow conditions and the body characteristics, it can start in a laminar regime and transition to a turbulent one. This matters for the drag study because at the laminar regime the boundary layer is thinner resulting in a less draggy characteristic if compared to the turbulent one. Therefore, methods for predicting and describing this phenomenon have been studied via numeric-computational, wind-tunnel testing and even in-flight approaches. The prediction to turbulence is still not fully comprehended so wind-tunnel testing is primordial to the study of the laminar to turbulence boundary layer transition in wings. Methods can couple the utilization of various techniques to either visualize this phenomenon or even quantify it. For this, infrared thermography, PIV, hot-wire anemometry and other techniques may be applied. Therefore, this article has the intention to provide a bibliographic review on the wind tunnel testing works for identifying the transition to turbulence on wings focusing on swept wings as a function of the Reynolds number and the techniques applied for each study. Some original data is also presented in this work. This article then can be used as a base reference that analyses the acknowledgments of each study and may contribute to future works on the subject.*

Keywords: laminar boundary layer, thermography, turbulence, drag force, swept wing

1. INTRODUCTION

In the flow passing over an aircraft, while the interaction of the wing with the air flow generates the lift necessary for it to remain in the air, there is also the generation of aerodynamic drag that opposes the movement of the aircraft itself. Both the drag force and the lift depend, in addition to other parameters, on the shape of the wing and its surface finish. Considering the operating flight regime of the aircraft, among the design characteristics of a wing, basically the optimum point is sought between the profile of the cross-section, the sweep angle, the twist of the wing, its tapering, and, of course, its wingspan and area to find the ratio that generates the greatest possible aerodynamic performance (generally, greater lift and less drag).

It is therefore known that an extremely thin layer of flow above the wing surface known as the boundary layer (BL) develops. In this region, the fluid starts from a non-slip condition and develops until it reaches the free flow velocity. Also, as the fluid travels across the surface of the wing, from the leading edge to the trailing edge, the boundary layer profile develops and almost always changes its thickness. Depending on the flow regime in terms of the Reynolds number and Mach number to which the wing is subjected, as well as external parameters, such as surface roughness, angle of attack and wing shape, the boundary layer transitions from the laminar regime for the turbulent, in addition to being able to suffer possible detachment from the body before reaching the trailing edge. In an illustrative way, Figure 1 points out these flow regions over an airfoil.

It is true to say that the detachment of the boundary layer has serious consequences for the operation of the aircraft, since the detachment area greatly affects the aerodynamic efficiency through the reduction of lift and consequent increase in drag due to the formation of a wide wake and intense detachment of vortices.

Nowadays, the set of wings of an Airbus A380 aircraft, for example, has dimensions close to a football field with an 80-meter wingspan and a wing area of approximately 845 m². However, the phenomena that occur in the boundary layer, among other factors, determine the performance of the aircraft, its ability to perform certain maneuvers, as well as its profitability, both in economic terms and in relation to environmental impacts, since the less drag is generated, the smaller the amount of fuel that must be used to carry out a given mission.

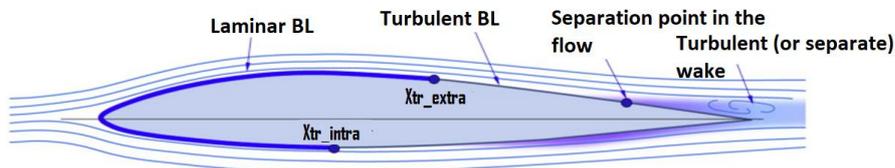


Figure 1. Main characteristics of a flow around an airfoil. Adapted from Gudmunsson (2013).

It is a fact that since the beginning of aviation, drag reduction has been one of the main objectives from a design point of view. An aircraft with lower drag is not only more economical in all respects, but also less harmful to the environment, which has become increasingly important in recent decades and will be even more important in the future. In addition to noise, emissions such as CO₂, NO_x and other pollutants, the focus is the emission of greenhouse gases into the atmosphere, which is directly linked to the burning of carbon-based fossil fuels (Beck et al., 2018). In quantitative terms, the transport sector alone contributed to more than 25% of greenhouse gas emissions in Europe in 2014, according to the European Union Statistical Service – EUROSTAT. A major bet in the transport sector is assumed by civil aviation, placing the efficiency of transport aircraft at the center of attention for urgent and high-impact scientific research. Thus, as seen, the considerable aerodynamic drag in modern aircraft is mainly due to the flow over the wings, which are normally placed at a swept or swept angle (Λ). Swept wings and supercritical profiles have expanded the speed envelope of modern aircraft, however there is room for substantial improvement in reducing aerodynamic drag by controlling laminar flow over them (Beck et al., 2018). It can be said that the boundary layer is turbulent on almost all wet surfaces of large aircraft. This results in viscous drag five to ten times greater than that considered in laminar flow. Figure 2 shows the division of drag, into its parts, for a typical civil aircraft, the Airbus A320, in cruise, as well as the potential drag reduction with possible technological improvements.

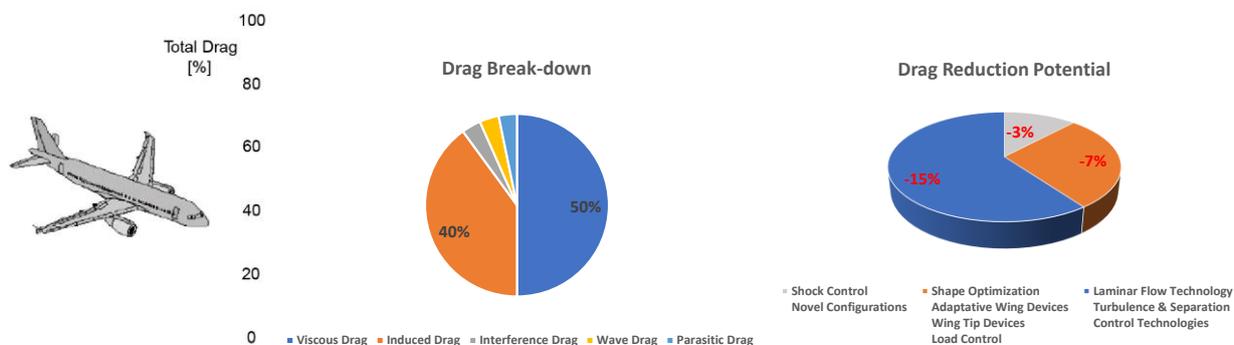


Figure 2. Drag analysis and technology opportunities for drag reduction. Adapted from Abbas et al. (2017).

From a technological point of view, with the control and possible delay of the laminar-turbulent flow transition on aircraft wings, it can potentially reduce aerodynamic drag by up to 15%, reducing emissions and fuel consumption considerably. The transition to turbulence in the boundary layers of swept wings has been the subject of much research in recent years. However, in real life is quite difficult to keep a whole wing surrounded by a laminar boundary layer. As said, many parameters could induce transition to a turbulent regime such as tridimensional flow over the spanwise direction, roughness of the wing, upstream turbulence, angle of attack among others. Based on this fact, a technological breakthrough could be achieved in finding a way to keep the boundary layer laminar over an entire cruise mission of an airplane. According to Dagenhart & Saric (1999), the process of minimizing aircraft drag by maintaining laminar flow by using active means such as suction, heating, or cooling is referred to as “laminar flow control (LFC).” LFC technology is being considered for applications on new large transonic and supersonic transport aircraft.

The understanding and control of the boundary layer transition process from laminar to turbulent in a swept wing are currently limited due to the difficulty of reproducing the phenomenon in the laboratory as well as the inability to measure it in space and time. The delay in the transition to drag reduction is further hampered by the lack of a simple and robust structure capable of suppressing the growth of primary and secondary crossflow instabilities. Additionally, theoretical, and numerical methods such Computational Fluid Dynamics (CFD) are also limited in tackling the transition phenomena

over swept wings due to not only the number of variables involved but also due to different instabilities mechanisms presents in the flow field.

One of the most recent projects to test laminar swept wing is the BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe) developed by Airbus. The aim of the project is to test laminar wing technologies in flight to reduce drag and increase aircraft energy efficiency. The BLADE project involves modifying an Airbus A340-300 aircraft with new blade-perfect wings and sensors to measure in-flight performance. The project is a collaboration between Airbus, the European Union and other companies and research institutions. However, this project has faced some practical difficulties such as cost for implementing the new technology in the operational field, weight of the wings since laminar wings are not necessarily lighter than conventional ones, maintenance since laminar wings will require more attention since they are more prone to damage in operation, operational feasibility since before full-scale implementation, blade wing technologies need to be tested and validated in real airline operations and influence of meteorological conditions since rain, turbulence and crosswind can affect the performance of laminar wings. Airbus had to develop technologies that allow laminar perfect wings to operate in variable conditions while maintaining flight efficiency and safety.

In Brazil, high-performance aerodynamics studies are quite scarce mainly due to the reduced number of medium-large wind tunnels, adequate instrumentation for proper measurements and lack of qualified human resources (researchers) in this study. This scenario has been changing in recent decades, mainly due to financial support through specific projects within the Brazilian aeronautical industry. In the last ten years, some projects were carried out in the country because of this investment, as well as those developed in laboratories or research centers through funding from research support foundations, such as FAPESP (in the state of São Paulo) and FAPEMIG (in Minas Gerais). Therefore, this article has the intention to provide a bibliographic review on the wind tunnel testing works for identifying the transition to turbulence on wings focusing on swept wings as a function of the Reynolds number and the techniques applied for each study. Some original data is also presented in this work. This article then can be used as a base reference that analyses the acknowledgments of each study and may contribute to future works on the subject.

2. PROBLEM'S DESCRIPTION

During and after the World War II the swept wings began to be used in aviation to overcome the problem of compressibility encountered at high-speed flights. It is known that near or supersonic speeds, shock waves will be formed over the wings, leading to a sudden increase in drag and a decrease in lift (loss of aerodynamic efficiency) while creates instability and control issues for the whole aircraft. Modern high-subsonic transport aircraft typically have wings sweeps in the range $\Omega_{LE} \approx [25^\circ, 35^\circ]$ in order to reduce wave drag at transonic speeds.

Figure 3 illustrates the classical representation of a swept wing and its effects on the critical Mach number (Anderson, 2011).

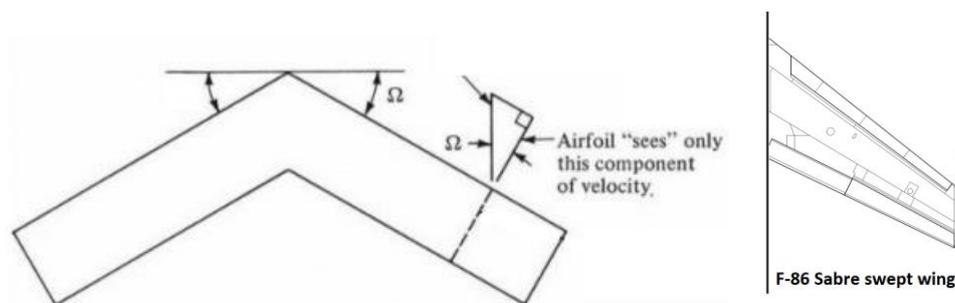


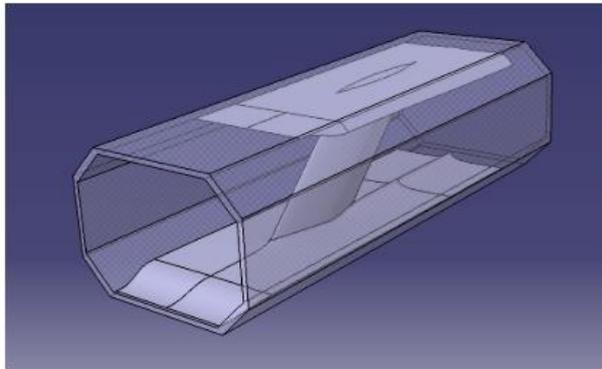
Figure 3. Classical representation of a swept wing and its effects on the critical Mach number.

The velocity vector that is seen by the wing is now, for the swept case, divided into two components. One is orthogonal to the leading edge, and the other one is parallel to it. Although the orthogonal component continues to, at least initially, present characteristics of the straight wing, with the boundary layer corresponding to a similar case as described on the previous section, there is now a parallel component, and soon it may entirely modify the boundary layer profile of the wing. Before the transition processes at straight wings reaches a certain stage, the boundary layer, even with the presence of the T-S instabilities may be considered as a 2-D profile. However, with the sweeping of the wing and the new velocity vector, the cross flow appears and thus, from the beginning, the boundary layer of swept wings is three-dimensional, which will add another kind of instability that act on this wing: the crossflow instability (CFI).

As mentioned, transport aircrafts will have swept wings ranging from 25 up to 35 degrees and then these angles are seen in most of the applied literature. Figure 4 reproduces some experimental setups used by Serpieri (2018), Soltani et al. (2013) and Borodulin et al. (2019), respectively, among several other authors.

As the wing is swept the flow becomes more three-dimensional over the wing as the sweep angle is increased. At the junctions with the side walls of the wind tunnel two types of aerodynamic problems are identified: (a) the wing is swept positively at one end while at the other end it is swept negatively. Many wind tunnel configurations use wall liners to

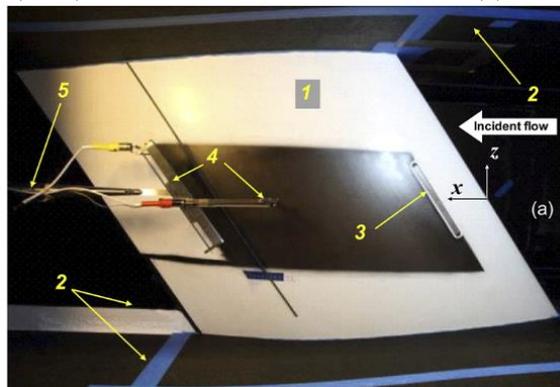
reduce this effect making the swept wing infinite. However, the effectiveness of the streamlined liners must be assessed by experimental tests.



(a) Serpieri (2018)



(b) Soltani et al. (2013)



(c) Borodulin et al. (2019)

Figure 4. Different wind tunnel setup for investigating transition phenomena on swept wings.

Figure 5 presents a general scheme used to describe the swept wing model and system of coordinates, as well as the main parameters associated with the problem. As with other aerodynamic problems, the Reynolds and Mach numbers, (Re) and (M), play a key role in describing the transition in swept wings. The Mach number (M) is relevant for transonic analyses. However, for low-speed wind tunnels the Mach number will not reach such values and the flow characteristics rely dependent of Re . Also, for comparisons purposes, the swept wing results to the straight wing case, the Reynolds number between the experiments must match so that only the sweeping angle (Ω) of the wing is presented as a difference for the transition front position (x_{tr}) between the cases and thus the crossflow instabilities problem would be isolated from the rest. The angle of attack (α) is another key parameter since the transition front moves according to the angle of attack since the pressure distribution and the way that the air interacts with the wing also changes, it is important to accomplish experiments covering the variation of this parameter.

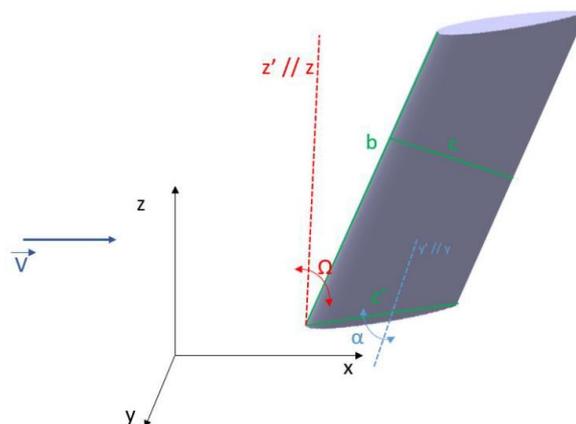


Figure 5. Axis system and main parameters: V = velocity; Ω = sweep angle; α = angle of attack; c = chord perpendicular to the leading edge; c' = chord; b = wingspan.

Finally, is the characterization of the boundary layer itself using anemometric sensors. If the boundary layer velocity profile is captured along the wing chord (c) it is also possible to estimate the fluctuations of the mean base flow and thus estimate the frequency of the instabilities present on the boundary layer that may influence the transition to turbulence.

3. THE TRANSITION PHENOMENA OVER SWEEPED WINGS

This section is devoted to concisely summarize the flow mechanisms and instabilities present in a swept wing and to present a literature review with the most recent scientific works developed in this field.

3.1 Flow mechanisms and instabilities

As reported by Dagenhart & Saric (1999), the boundary-layer transition problem usually consists of three important phases: (a) receptivity; (b) linear disturbance amplification; and (c) nonlinear interaction and breakdown (Morkovin, Reshotko & Herbert, 1994).

It is known that the receptivity is the process by which disturbances in the external environment enter the boundary layer to begin the transition process (Morkovi, 1969). These external disturbance mechanisms are related to free-stream turbulence being associated to vortical and acoustic modes as well as wing surface irregularities and roughness, and surface vibrations. These small disturbances provide the initial amplitude conditions for unstable waves.

The nonlinear interaction and breakdown phase of the transition problem begins when the individual modes attain sufficient magnitude that products of the disturbance components can no longer be neglected as being small when compared with the base flow - Dagenhart & Saric (1999). At this stage, the disturbances may have become so large that they begin to severely distort the base flow either spatially or temporally.

When considering the flow over a swept wing, the laminar boundary layer has four fundamental instability modes: (a) Tollmien-Schlichting or streamwise; (b) crossflow; (c) centrifugal or Grötler instability and (d) attachment line. These modes may exist independently or in combinations.

The Tollmien-Schlichting instabilities (T-S waves) appear due to the parietal characteristic of the boundary layer. They are vortices structures that are advected by the boundary layer in the streamwise direction, appearing by the amplification of instabilities in which a determined wavelength is select by the flow to be the most amplified one. They are then amplified when the pressure gradient in the streamwise direction is positive and are very receptive to acoustic and vortical free-stream disturbance by a process where, due to viscosity effects, a portion of the energy of the flow is passed to the instabilities. Thus, the relation between cinematics and viscous effects may determinate if the T-S instabilities are going to be attenuated or amplified. Thereby, differently from other transition mechanisms, there is no need for the appearing of an inflectional velocity profile. Then, as these instabilities move downstream, their structures grow in amplitude as the advection velocity decreases due to the thickening of the boundary layer. As consequence, vortices structures that are close to each other may collapse and merge, generating larger whirl structures at double wavelength, phenomenon known as vortex pairing. Then, secondary mechanisms cause the flow breakdown, creating complex structures that cannot be referred to as presenting a two-dimension characteristic anymore. Until the full turbulent state is reached, the evolution of the T-S waves may pass through some intermediate states, evolving in the streamwise direction to complex structures called horseshoes and Λ -structures, evolving until the appearing of the called turbulent spots until the full breakdown.

The crossflow instabilities (CFI) happen at the orthogonal direction to the wing due to the orthogonal velocity component that induces the apparition of co-rotating whirl structures that are aligned with the flow direction. The crossflow instability was first identified by Gray (1952) when he found that high-speed swept wings had only minimal laminar flow even though unswept versions of the same wings had laminar flow to approximately 60 percent chord. In regions where the flow is accelerating, these structures may increase in amplitude, traveling on the spanwise and streamwise when the streamwise turbulence direction is high, or they remain stationary when the streamwise turbulence direction is low. This effect also induces the crossflow vortices (CFV) amplitude to increase when approaching the trailing edge. Also, the CFV may serve as secondary mechanisms to accelerate or to induce the transition to turbulence on the streamwise direction, as they alter the mean flow field introducing a velocity profile with at least one inflection point, that, besides not being sufficient to the turbulence to initiate, are mandatory for the transition in some kinds of flow, and now they make it possible to appear inviscid instabilities modes at the boundary layer, increasing its instability characteristic, and may advance the transition front location if compared to a wing with no crossflow. They can also present a travelling or stationary nature. Figure 6, adapted from Serpieri (2018), represents a schematic comparison between both T-S waves and CFI in terms of the direction they follow on the wing boundary layer.

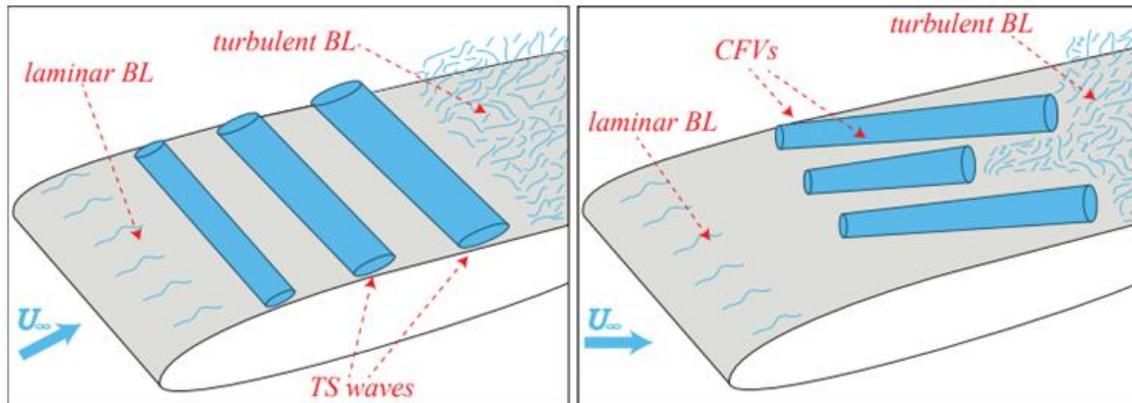


Figure 6. Schematic comparison between both T-S waves and CFI path over the wing. Adapted from Serpieri (2018).

Comparing the contribution of the T-S waves and the CFI to the turbulence transition processes, an early analysis may be done concerning the magnitude of the sweep angle and the pressure gradient. Thus, for favorable negative stream wise pressure gradients with an inflection point in the velocity profile, and sufficiently large sweep angles, something starting around 20°, the predominance of the stationary or traveling CFI is expected. For low turbulence means, the stationary CFI are predominant, while higher turbulent environments are more prone to a travelling CFI type. However, for weak chordwise adverse pressure gradients, the T-S waves influence may be predominant - Borodulin et al. (2019). Figure 7 represents the wing (consider it to be with a swept angle applied) demonstrating the velocity profiles of both orthogonal and parallel components, as much the direction followed by the T-S waves and the CFI. It is also possible to verify the inflectional characteristic of the medium velocity profile on the spanwise direction due to the crossflow.

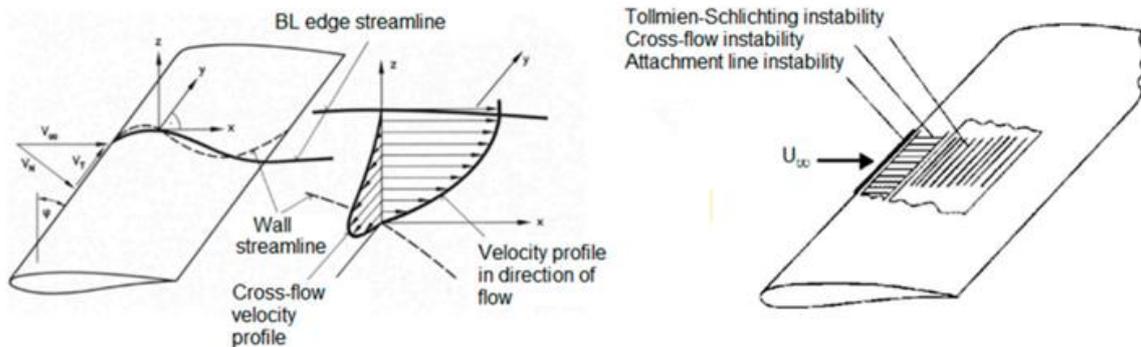


Figure 7. 3D Boundary Layer on a Swept Wing and Transition Mechanisms. After Beck et al. (2018).

The Görtler instability has both centrifugal and parietal characteristics. It happens inside the boundary layer in secondary flows only if the wall is concave and if the boundary layer thickness is comparable to the wall curvature. At a stable environment, a centrifugal force field appear due to the wall curvature, and it is counterbalanced by a pressure gradient that points from the wall to the curvature center. If this equilibrium is broken, the Görtler instabilities may appear with a counter rotating behavior. A scheme of the Görtler instabilities is presented on Fig. 8. For the Görtler instabilities to be manifested on wings, usually the airfoil camber must be prominent or at least some part of the airfoil must present a concave geometry. Either way, if manifested, due to conventional wings projects, the concave part of the airfoil is in the lower surface, so the Görtler instabilities should be located there.

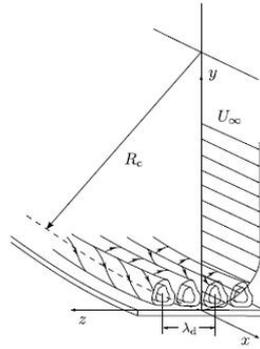


Figure 8. Görtler instabilities scheme. Adapted from Saric (1994).

The attachment line instability transition mechanism may happen on swept bodies when the leading-edge curvature is small, so that the ratio between the leading-edge thickness and the wing chord is less than 1%. It appears due to the splitting of the airflow that reaches the leading edge into the upper and lower surface of the wing and acts on the spanwise direction – Poll (1979). This can cause the development of a boundary layer along the attachment line that can become unstable and so contaminating the overall boundary layer since the beginning of it – Fig.9. Especially at scaled wing models for wind tunnel testing, the possibility of this transition mechanism must always be considered to occur. At fully aircraft models, the Attachment Line instability may also appear in the junction of the fuselage to the wing, travelling on the span direction and contaminating the boundary layer of the wing.

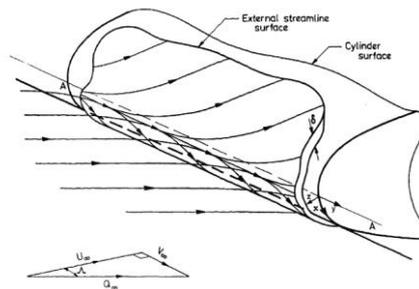


Figure 9. Attachment line instabilities scheme. (Poll 1979; reproduced by kind permission of The Royal Aeronautical Society's Aeronautical Journal).

3.2 Recent literature review

As already summarized, the motivation for studying the boundary layer transition from laminar to turbulent regime comes from the need to reduce drag on aircraft by allowing the boundary layer to remain for a greater extent of the wing chord in laminar regime. However, since this phenomenon is still not easily modeled by computational techniques, most studies in the area are not just computational, involving also or solely testing models of scaled wings in wind tunnels so that a more concrete and physical analysis can happen. Still, the researchers' objective is not limited to just knowing the transition mechanism of the boundary layer regime. The final objective is, in fact, to propose operational techniques to control this mechanism.

In this way, Serpieti (2018) studied the instability phenomena that occur in the boundary layer of swept wings and the way that these mechanisms affect the transition of the boundary layer from the laminar regime to the turbulent. Still, Serpieti (2018) proposed ways to control such mechanisms to condition the boundary layer regime transition through Alternating Current Dielectric Barrier Discharge Actuators. The study experiments took place in a closed-circuit wind tunnel with a t-section and tests measuring 1.25 m x 1.80 m x 2.6 m and a swept wing model with a 1.25 m span and 1.27 m of chord, whose cross section corresponds to a modified NACA66018 airfoil. For the characterization of the flow around the swept wing model, the author used the following techniques: visualization of the oil flow, which reveals the points of detachment of the boundary layer by the wing; visualization of the flow through infrared thermography, to determine the areas of laminar and turbulent regime of the boundary layer, and thus the transition point of the regime; and hot wire anemometry, PIV (Particle Image Velocimetry) and Tomography-PIV to determine the magnitude and velocity profile of the flow.

Kurz (2017) studied the application of plasma dielectric actuators to control the boundary layer transition via in-flight tests. The purpose of this work was to analyze the operation of dielectric actuators in real flight conditions. For this purpose, the equipment for carrying out the experiments was assembled in such a way that it could be used both in the wind tunnel and in the GROB G109b single-engine aircraft model. In this way, the study demonstrated the delay in the

transition of the boundary layer regime both in the wind tunnel and in typical atmospheric flight conditions. Thus, in order to be able to use the plasma actuators and simulate a flight regime related to that of a small civil aircraft, a wing prototype was built, based on the laminar airfoil BU84-158, to be coupled both to the wing of the tested aircraft and to the wind tunnel tests – Kurz (2017).

Wang et al. (2018) proposed the numerical study of the effect of dielectric-barrier-discharge (DBD) plasma actuators on the control of boundary layer crossflow instability in the transition from laminar to turbulent regime in a swept wing using a nonlinear method of stability (nonlinear parabolized stability equation -NPSE), comparing numerical results with experimental results. Thus, they proposed a wing with a cross-section corresponding to the NLF-0415 airfoil, designed with 45 degrees of sweep and a 4 degrees of attack angle with the dielectric actuators placed close to the leading edge. The idea proposed by the authors was to use the actuators to generate, through electricity, a disturbance that opposes the crossflow vortices, reducing the energy present in the vortices that influence the transition of the boundary layer regime. The experiments were carried out using a wind tunnel with a closed section measuring $1.2 \text{ m} \times 1.2 \text{ m} \times 3 \text{ m}$, with the wing at 45 degrees of sweep and 1.2 m of chord. Wang et al. (2018) tested the use of actuators to generate control disturbances in a harmonic and subharmonic way. For the first form, it was concluded that the method used is not robust enough because, to be effective, it must know exactly where the instability occurs, which is not possible to happen operationally. The second form was able to effectively reduce the energy of crossflow instabilities in a practical and operational way.

Through computational methods, Zhenrong & Huang (2016) studied the correlation between the lift coefficient, the sweep angle, and the angle of attack when considering the point of transition from laminar to turbulent regime of the boundary bed since it can be modified by sweeping compared to a straight wing. For this purpose, a RAE2822 subcritical airfoil wing was used. According to the study, by increasing the angle of attack, the disturbances on the upper face of the wing become more unstable, causing the boundary layer regime transition point to approach the leading edge. Furthermore, it was found that the higher the lift coefficient, the lower the attack and sweep angles need to be for the regime transition to occur.

Beck et al. (2018) studied ways to decrease surface drag through boundary layer suction techniques throughout the wetted area of an aircraft to ensure that it remained in laminar regime for longer. The laminar flow control technique was tested for a generic fuselage model associated with existing airfoil profiles. The study was carried out by computational methods through software such as XFOILSUC and Matlab and through RANS simulations but based on experimental results from previous works. The results showed that, for example, for the supercritical airfoil DLR F15 at Mach 0.7 and Reynolds number of 30 million, the applied suction delayed the boundary layer regime transition by 85% for the upper and lower side of the airfoil.

As another form of boundary layer control aimed at reducing drag, Zhang & Yin (2019) studied the use of riblets and their relationship with the sweep angle. Using a passive method of flow control, the proposed idea is that the grooves can restrict the turbulent structures within the boundary layer and, thus, decrease the emission of vortices that contribute to the energy loss of steady state flow in the boundary layer and thus reducing surface drag. The work was conducted computationally, whose analysis method was validated in previous works by the authors themselves. Regarding the flow influence due to the sweep angle, it was found that the cross flow lost strength compared to the wing without grooves, and it was considered weak except in the areas close to the leading and trailing edges, causing a considerable decrease in drag. Furthermore, it was observed that in this case, the surface drag decreased, and the pressure drag increased.

Hirokawa et al. (2020) studied the reduction of surface drag on a straight wing with a cross-section corresponding to the Clark-Y airfoil by a passive blowing method for flow control. The study was conducted by computational methods and experimental techniques in a wind tunnel, with a wing model of 0.4 m of chord by 0.548 m of wingspan. To passively generate blowing, a tubular system was installed which, close to the leading edge creates a suction area, and close to the rear of the upper part of the wing generates an exhaust area. Thus, the pressure differential causes the injection of air to occur without the need for an active mechanism for this. Thus, modifications of the velocity profile over the wing were observed, which were responsible for reducing the frictional drag. It should be noted that the authors observed a difference in the computationally obtained data versus the experimental data and delegated this difference to the model blocking ratio in relation to the wind tunnel.

There are many possibilities to be studied to reduce frictional drag on aircraft wings. In another example, in addition to the studies, Alderman et al. (2016) analyzed the use of the '*Gaster Slot*', a device placed on the leading edge that reduces contamination of the boundary layer by structures with turbulent characteristics, decreasing the thickness of the boundary layer.

4. SOME RESULTS AND DISCUSSION

To give a glimpse of the present authors research in the boundary layer transition front determination of a swept wing model, some results are next presented. The study was conducted as a partnership between researchers from the Universidade Federal de Uberlândia (UFU) and the Universidade de São Paulo (USP-São Carlos) at the LAE-1 research center. The facility is equipped with a large blown-down closed-circuit wind tunnel with a $1.68 \text{ m} \times 1.29 \text{ m} \times 3.00 \text{ m}$ test section, allowing maximum speeds of around 40 m/s. There, a swept wing model of 25° of swept angle, 1.434 m of

wingspan (1.29 m in the orthogonal direction to the test section floor) and with 0.5 m of chord (perpendicular to the leading edge), manufactured in fiber glass, was experimented under a thermography camera aiming to detect the transition front location of the boundary layer, as depicted by Fig.10.



Figure 10. Experimental setup for measuring the BL transition over a swept wing ($\Omega = 25^\circ$) with IR thermography.

The laminar and the turbulent portion of the boundary layer present different heat emission intensity that can be translated by the infrared camera in a greyscale image, allowing the identification of the transition front location. To increase the contrast between each portion of the wing, the model is heated, leaving it hotter than the surrounding environment. Thus, since the turbulent portion has a higher diffusive capability, it will cool faster than the laminar portion, being registered as a darker tonality at the infrared image. Later, an image processing code is used to better identify the transition location in terms of the chord length. Thereby, the model has been tested for a variation of Reynolds Numbers and angles of attack aiming to verify the influence of these factors on the transition front location of the swept wing. Also, these data have been compared to a correspondent straight wing to study the crossflow influence on the transition location. For the present article, the results of the swept wing model are presented for a Reynolds of 915000 and angles of attack of 2° and 3° - Fig.11. The transition front has been found to be located at 53.5% and 45.6% of the chord respectively.

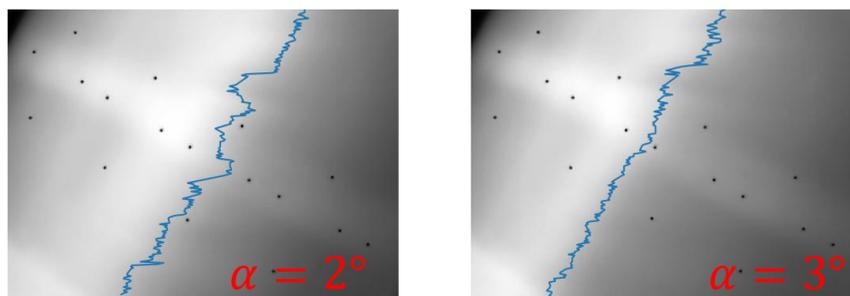


Figure 11. Swept wing infrared image for boundary layer transition location identification at $\alpha = 2^\circ$ and 3° (flow from left to right).

By inspecting the IR images on Fig. 11, it reveals that in general, increasing the angle of attack is moving the transition front closer to the leading edge of the wing. Also, it is easy to see that the heating method applied to increase the IR image contrast was well served since even with the raw IR image it is possible to recognize the transition front position. Although, a processing image code has been written in Python to better characterize the transition front and to quantify it in terms of percent of chord (x_{tr}/c), as illustrated by the blue line. Thus, the line represents the transition front from laminar to turbulent, even though it is not a perfect straight line since the transition front is dynamic and may change if the initial flow condition is not kept with no major variations during the experiment. In keeping the flow conditions duly controlled, the transition front is representative of a mean pattern along both the chord and the wingspan.

As well-known, a turbulent boundary layer presents higher viscous efforts than the laminar one, culminating in a higher viscous drag force component. Thus, the understanding of the transition process to turbulence opens the possibility to boundary layer control to propose mechanisms which aim to oppose the evolution of the instabilities that promote the boundary layer transition to turbulence. However, before proposing such flow control devices, the transition mechanisms

must be understood. Thereby the present work has studied the identification of the boundary layer on a swept wing model aiming to identify the behavior of the transition front position through infrared thermography technique. The present work is expected to serve as a foundational step for future research, facilitating a deeper understanding of wing turbulence transition. This understanding can be achieved through a combination of material experimentation and numerical-computational simulations. This progress will enable Brazilian laboratories to develop and propose active flow control devices and techniques. Furthermore, this work can be utilized as a tool to attract investments for laboratories involved in acquiring new equipment essential for studying boundary layer transition mechanisms.

5. ACKNOWLEDGEMENTS

We thank Prof. Fernando Martini Catalano for providing the lab floor and equipment used to make this collaboration possible. This work was funded by FAPEMIG under grant number APQ-01589-21 “Investigação Experimental do Fenômeno de Transição Laminar-Turbulenta em Asa Reta e Enflechada”.

6. REFERENCES

- Abbas, A., Bugada, G., Ferrer, E., Fu, S., Periaux, J., Pons-Prats, J., ... & Zheng, Y. (2017). Drag reduction via turbulent boundary layer flow control. *Science China Technological Sciences*, 60, 1281-1290.
- Airbus’ “BLADE” laminar flow wing demonstrator makes first flight | Airbus. Disponível em: <<https://www.airbus.com/en/newsroom/press-releases/2017-09-airbus-blade-laminar-flow-wing-demonstrator-makes-first-flight>>.
- Alderman, J. E., Rolston, S., Gaster, M., & Atkin, C. J. (2016). A method of Reducing the Drag of Transport Wings. In *34th AIAA Applied Aerodynamics Conference* (p. 3115).
- Anderson, J. (2011). *EBOOK: Fundamentals of Aerodynamics (SI units)*. McGraw hill.
- Beck, N., Landa, T., Seitz, A., Boermans, L., Liu, Y., & Radespiel, R. (2018). Drag reduction by laminar flow control. *Energies*, 11(1), 252.
- Borodulin, V. I., Ivanov, A. V., Kachanov, Y. S., Mischenko, D. A., Örlü, R., Hanifi, A., & Hein, S. (2019). Experimental and theoretical study of swept-wing boundary-layer instabilities. Three-dimensional Tollmien-Schlichting instability. *Physics of Fluids*, 31(11), 114104.
- Dagenhart, J. R., & Saric, W. S. (1999). *Crossflow stability and transition experiments in swept-wing flow* (No. NASA/TP-1999-209344).
- Gray, W. E.: The Effect of Wing Sweep on Laminar Flow. Tech. Memo. Aero 255, British R.A.E., Feb. 1952.
- Gudmundsson, S. (2013). *General aviation aircraft design: Applied Methods and Procedures*. Butterworth-Heinemann.
- Hirokawa, S., Eto, K., Fukagata, K., & Tokugawa, N. (2020). Experimental investigation on friction drag reduction on an airfoil by passive blowing. *Journal of Fluid Science and Technology*, 15(2), JFST0011-JFST0011.
- Kurz, A. (2017). In-flight application of dielectric barrier discharge plasma actuators for active wave control.
- Morkovin, M. V., Reshotko, E., & Herbert, T. (1994). Transition in open flow systems—a reassessment. *Bulletins of the American Physical Society*, 39(9), 1882.
- Morkovin, M. V.: On the Many Faces of Transition. *Viscous Drag Reduction*, C. Sinclair Wells, ed., Plenum Press, 1969, pp. 1–31.
- Poll, D. I. A. 1979 Transition in the infinite swept attachment line boundary layer. *The Aeronautical Quarterly* 30, 607–629.
- Saric, W. S. (1994). Görtler vortices. *Annual Review of Fluid Mechanics*, 26(1), 379-409.
- Serpieri, J. (2018). *Cross-Flow Instability: Flow diagnostics and control of swept wing boundary layers* (Doctoral dissertation, Delft University of Technology).
- Soltani, M. R., Masdari, M., & Damghani, H. (2013). Experimental investigation of leading-edge roughness effects on stationary crossflow instability of a swept wing. *Scientia Iranica*, 20(3), 524-534.
- Wang, Z., Wang, L., Wang, Q., Xu, S., & Fu, S. (2018). Control of crossflow instability over a swept wing using dielectric-barrier-discharge plasma actuators. *International Journal of Heat and Fluid Flow*, 73, 209-222.
- Zhang, Y., & Yin, Y. (2019). Study on riblet drag reduction considering the effect of sweep angle. *Energies*, 12(17), 3386.
- Zhenrong, J. I. N. G., & Huang, Z. (2017). Instability analysis and drag coefficient prediction on a swept RAE2822 wing with constant lift coefficient. *Chinese Journal of Aeronautics*, 30(3), 964-975.

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