

EXPERIMENTAL INVESTIGATION OF WISHBONE VORTEX GENERATOR EFFECTS ON THE NACA 4412 AIRFOIL AT LOW REYNOLDS NUMBERS

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Abstract

This study presents the results of an experimental wind tunnel campaign investigating the aerodynamic performance of the NACA 4412 airfoil equipped with wishbone-type vortex generators (VGs) at low Reynolds numbers. The primary objective is to quantify the improvement in aerodynamic efficiency achieved using VGs within the Reynolds number range not previously studied of 3×10^4 to 1×10^5. Two VG heights ($h/c = 0.15, h/c = 0.3$) were tested, along with variations in their longitudinal placement ($x/c = 0.15$ to 0.21). The results reveal a strong dependence of VG effectiveness on Reynolds number. At very low Reynolds numbers ($< 5 \times 10^4$), aerodynamic efficiency improvements of up to 100% are observed, indicating significant delay in flow separation. In contrast, for higher Reynolds numbers approaching the improvements are more modest, typically in the range of 5–10%. Additionally, the optimal VG configuration is found to largely vary with Reynolds number, with larger VG heights providing better performance as Reynolds number decreases. These findings highlight the importance of tailoring VG geometry and placement to the operating flow regime, particularly for low-Reynolds-number applications such as UAVs and small-scale aerodynamic devices, a case study largely omitted until now.

Keywords: vortex generator; low Reynolds airfoils; LSB

1. Introduction

This work focuses on the experimental characterization of the NACA 4412 airfoil in the low Reynolds number regime, as well as on assessing the impact of Vortex Generators (VG) on its aerodynamic performance. Below Reynolds numbers of $\mathrm{Re} = 10^6$, the lift and drag characteristics of an airfoil can no longer be assumed constant with respect to variations in Reynolds number. As Re decreases, the aerodynamic behavior of the airfoil deteriorates: drag increases while the maximum lift coefficient decreases. Both effects arise from complex physical mechanisms developing within the boundary layer. The behavior is particularly influenced by shifts in the laminar–turbulent transition point and by the formation of laminar separation bubbles (LSBs), which lead to nonlinear lift curves and a significant increase in drag.

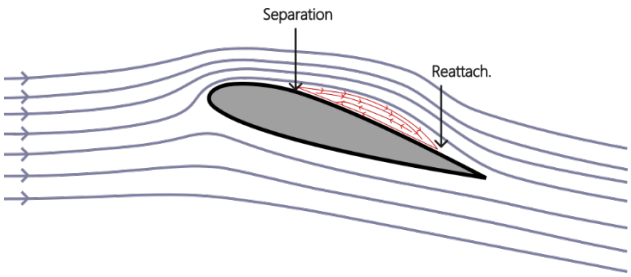


Figure 1 – Formation of a Laminar Separation Bubble (LSB) on the airfoil upper surface

Ideally, if the transition to turbulence can be triggered upstream of the point where the LSB would naturally form, its development can be suppressed, thereby improving the aerodynamic performance of the airfoil at low Reynolds numbers. This concept underlies the development and use of vortex

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generators (VGs), passive flow-control devices that create streamwise vortices to mix high-momentum outer-flow air with the low-energy boundary layer, delaying or preventing separation and/or the formation of the LSB [1]. Traditionally, vortex generators have been widely applied on wind-turbine blades, particularly near the root region, to enhance lift and reduce stall. However, the increasing relevance of low-Reynolds-number aerodynamics in applications such as electric aircraft and small unmanned aerial systems has opened new opportunities for their use. In this context, the present study aims to characterize both the NACA 4412 airfoil and the effect of vortex generators within this low-Reynolds-number regime. It is worth noting that, although the use of VGs has been widely studied in the literature in the context of low Reynolds airfoils, the term “low” does not usually refer to Reynolds numbers lower than 10^5 [2]. That is why, considering how sensitive airfoil performance is at Reynolds number below that number, a specific analysis shall be done to check if well documented performance gains at higher Reynolds number can also be achieved.

2. Experimental Setup and airfoil selection

The experimental campaign was conducted in the low-Reynolds-number wind tunnel at the University of León depicted in Figure 2. The facility operates at wind speeds below 5 m/s and turbulence intensities under 0.5%, enabling Reynolds numbers between 4×10^4 and 1.1×10^5. The test section has a crosssectional area of 0.54 m² (60 × 90 cm), allowing achievable flow velocities ranging from 3 to 7 m/s. The wing model used in the tests has a span of 60 cm and a chord of 25 cm. The airfoil was manufactured from expanded polystyrene and finished with a polishable sealant to ensure both low weight and a smooth surface.

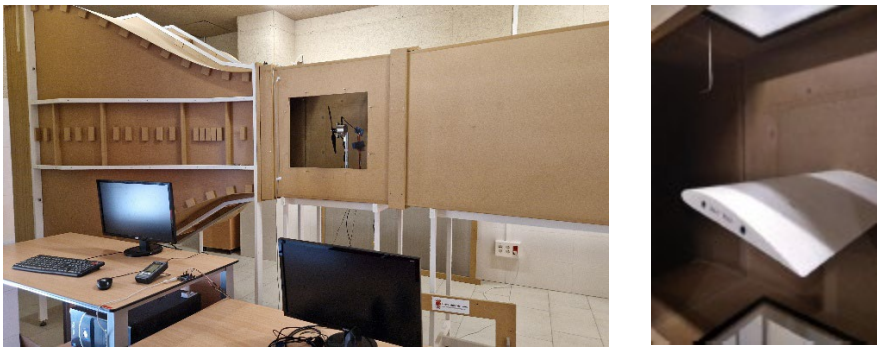


Figure 2 – Low-Reynolds-number Wind Tunnel at the University of León

The NACA 4412 airfoil was selected because it has been widely studied in previous works within the low-Reynolds-number regime, both experimentally and computationally, and has consistently demonstrated high aerodynamic efficiency under these conditions. Its behavior in laminar-dominated flows, including the formation and evolution of laminar separation bubbles, is well documented in the literature, making it a reliable and widely accepted reference case. This is illustrated in Figure 3, which shows the lift coefficient at Re = 75,000, comparing measurements obtained in the University of León wind tunnel with data from Koca et al. [4], Simons [5], and Abbott & von Doenhoff [6], as well as XFOIL predictions. As can be observed, there is significant variability among the datasets, likely caused by differences in turbulence intensity and surface finish, highlighting the performance sensitivity of this airfoil under low-Reynolds-number conditions. This high sensitivity underscores the need for a more detailed characterization of the low-Reynolds-number behavior of this class of airfoils.

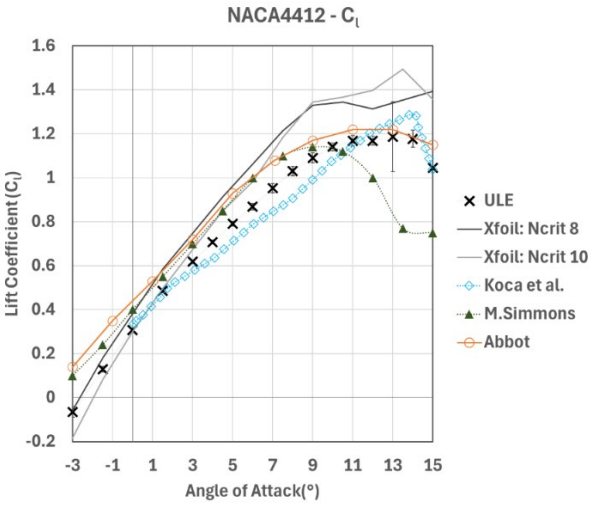


Figure 3 – Lift coefficient of the NACA 4412 at Re = 75,000, measured in the University of León low-speed wind tunnel (ULE), and compared against XFOIL predictions (Ncrit = 8, 0.106 % turbulence level; Ncrit = 10, 0.046 % turbulence level) as well as experimental data from Koca et al. [4], Simons [5], and Abbott & von Doenhoff [6].

3. Vortex Generators for performance improvement

It is a well-documented issue that VGs performance strongly depends on their geometry, size or exact location. A careful analysis is now carried out to decide on those different aspects.

3.1 Selection of the Vortex Generator type

Classical designs include triangular, rectangular, and trapezoidal vanes, as well as dome-type and convergent–divergent shapes, each producing distinct vortex structures that vary in strength, coherence, and drag penalty. More recent developments have explored configurations with multiple legs or split surfaces to improve vortex stability and reduce interference effects. Within this context, the wishbone-type VG [1] stands out for its bifurcated, Y-shaped layout, in which two inclined legs rise from a common root to generate a coherent counter-rotating vortex pair (see Figure 4). This geometry provides a smoother and more sustained vorticity distribution compared to single-fin VGs, making it an appealing option for applications where efficient boundary-layer energization is required with minimal additional drag.

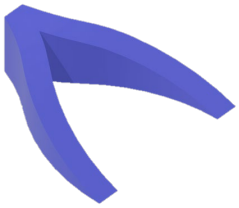


Figure 4 – Final wishbone design ready to be produced by additive manufacturing means.

For the present study, the conventional-scale wishbone VGs have been adopted to ensure a strong and persistent vortex system suitable for the low-Reynolds-number operation of the NACA 4412 airfoil, while also minimizing the complexity of integration into the experimental setup. Their planar surfaces and single base attachment make them straightforward to fabricate, although the very small size required at very low Re number represents an important challenge.

Wind tunnel model has a chord of 250mm thus, according to the literature, the wishbone VG has an height h of 1mm and 3 mm wide (see section 3.3), making it almost impossible to manufacture with the required accuracy just by using the more conventional fused filament printer. Then, it was necessary to employ the more complex but highly accurate SLA (Stereolithography) technique, that

uses a UV laser to cure liquid resin layer by layer, creating highly detailed and precise 3D objects. Once the VGs are manufactured, they are easy to bond flush onto the airfoil. This combination of adequate structural robustness, low installation effort, and favorable aerodynamic behavior made the wishbone configuration an efficient and practical choice for the boundary-layer control objectives of this work. Both forward-facing (with the tip pointing upwind) and backward configurations were tested; however, only the results for the forward-facing configuration are presented here, as it yielded better performance.

3.2 Selection of the Vortex Generator chord location

As previously pointed out, it is a well-known issue that the position selected for the VGs (as a percentage of the airfoil chord) has a critical effect on airfoil performance. Thus, two different locations have been tested. One of them located at $x/c = 0.21$ (where x is the distance from the leading edge and c is the airfoil chord), very close to the location at which the LSB is expected to appear at the most relevant angles of attack (in the range from 3 to 8 deg). In order to properly test performance sensitivity to chord location (probably the most critical parameter) another location is selected closer to the leading edge, to be more precise at $x/c = 0.15$. The new proposed location should make it possible to have a larger distance for the development of stronger vortices capable of more decisively altering the appearance and/or location of the laminar separation bubble. On the other hand, this new location may trigger earlier laminar to turbulent transition.

The span of the wind tunnel test section is 0.6 m, and the vortex generators were located at a spanwise spacing of $4h$, following standard recommendations.

3.3 Selection of the Vortex Generator size

Final parameter to be decided is VG size. The capability of the VG to generate vorticial flow structures and introduce momentum from upper layers on lower boundary layers is given by its size. A common practice in literature is to set the VG height as a fraction of the boundary layer height. Following the recommendations that can be found in [7], the height is selected in the range $0.1\delta - 0.3\delta$ (where δ is the local thickness of the boundary layer) to keep a low profile and minimize drag penalty. It should be noted that boundary layer thickness changes depending on the Re to be tested and the angle of attack. Thus, a value in the middle of the range (i.e. 0.2δ, $Re = 60000$, 0.1% turbulence level, $\alpha = 5°$) is selected to keep within the desired design region for most of the tested conditions. This translates to a height of 1.125 mm, and a length and width of 3 mm (to maintain proportions for the selected wishbone design).

Once the first set of tests were done, it seemed that VGs were underperforming for the lowest Re we tested. This is likely because, at low Reynolds numbers, additional momentum must be transferred from the outer flow into the boundary layer. As this may be caused by an insufficient height, a new batch of test was done by increasing the size of the VGs to twice the original one.

4. Results analysis

The results that can be seen in Figure 5, correspond to full set of tests that have been performed within the context of this work. At the top of the figure, the aerodynamic efficiency ($\eta = c_l/c_d$) of the NACA 4412 airfoil for Reynolds numbers between 30,000 and 100,000 can be seen. In the middle of the figure, the results correspond to the use of regular size (1.1 mm height) VGs at 0.15 and 0.21 x/c. Finally, in the lower part of the figure, performance achieved when using the larger VGs is displayed.

In the baseline configuration, aerodynamic efficiency peaks at 5° angle of attack, reaching values close to 30 for Re = 100,000, while lower Reynolds numbers exhibit significantly reduced performance. When vortex generators are installed, the efficiency curves shift upward for all Reynolds numbers but the largest one, particularly in the mid-range angles of attack, indicating a clear improvement in flow attachment and delaying separation. The most relevant changes occur at the lower Reynolds numbers (between 30,000 and 50,000), where the improvement in aerodynamic efficiency is substantial compared to the baseline case. This analysis is true for almost any tested configuration, although important differences can be found between the different cases when, subsequently, attention is paid to the details.

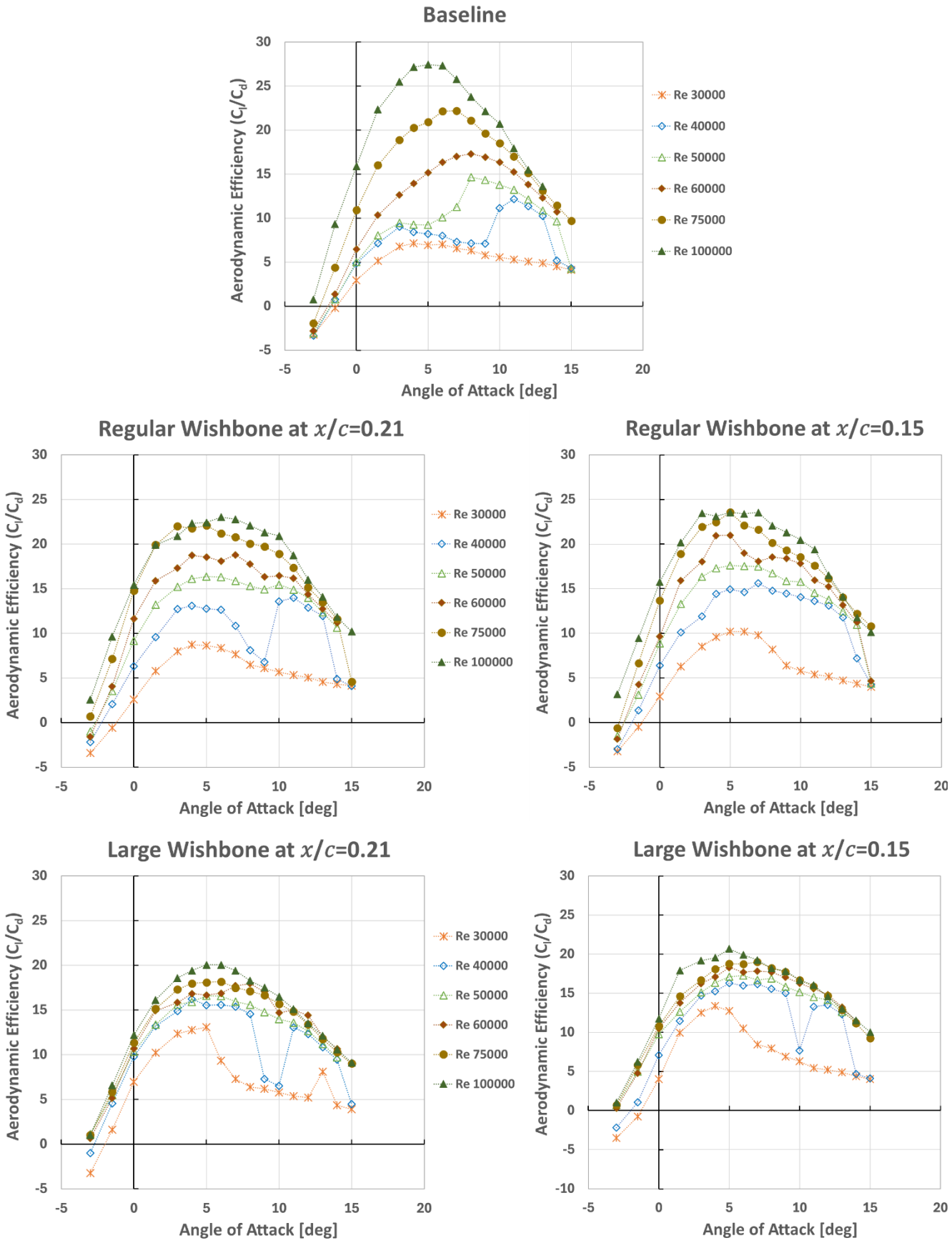


Figure 5 – Aerodynamic efficiency of the NACA 4412 airfoil at low Reynolds numbers (30,000–100,000) without vortex generators (top), with regular size vortex generators installed at $x/c = 0.21$ (mid left) and $x/c = 0.15$ (mid right), and with larger size vortex generators installed at $x/c = 0.21$ (bottom left) and $x/c = 0.15$ (bottom right)

Although further investigation is required, the data reveals a highly sensitive, non-linear interaction between the VGs and the boundary layer at $Re = 40{,}000$. Specifically, an angle of attack of $10°$ marks a critical performance dip where a LSB forms, leading to a sudden decrease in efficiency. Interestingly, this degradation is transient, as the LSB is mitigated and recovers at $12°$. We hypothesize that this behavior is driven by the chordwise migration of the separation point relative to the fixed VGs. At $10°$, the natural separation point likely coincides unfavorably with the VG placement (either engulfing the VGs or occurring just downstream) which dampens vortex strength and allows a LSB to develop. However, as the angle increases to $12°$, the steeper adverse pressure gradient forces the initial separation point further upstream. This geometric shift allows the VGs to fully interact with the separated shear layer, triggering rapid turbulent mixing and forcing flow reattachment, thereby restoring aerodynamic efficiency.

For a better insight into the effect of the VGs, we will compare the experimental improvements obtained with the vortex generators with the theoretical results predicted by traditional viscous panel methods, such as XFOIL, when the transition point is forced at the same chordwise location. Results are shown in Figure 6 for an angle of attack of 5°, approximately the point of maximum aerodynamic efficiency. The comparison includes the Reynolds numbers from 30,000 to 75,000, two chordwise positions ($x/c = 0.21$ and $x/c = 0.15$) and the two proposed sizes for the VGs. Regarding the regular size VG (that is, the smaller one, light blue color in Figure 6) the experimental data shows reasonable agreement with the theoretical trends for Reynolds number of 50,000 and higher. However, performance notably drops for Re = 30,000 and 50,000. This encouraged us to test the hypothesis already pointed in 3.3 of using larger VGs for better results at very low Reynolds. The larger devices (dark blue lines in Figure 6) produce a more substantial change on the flow structure, the result is that the performance improvement is higher for the lower Reynolds numbers but worse for the larger ones.

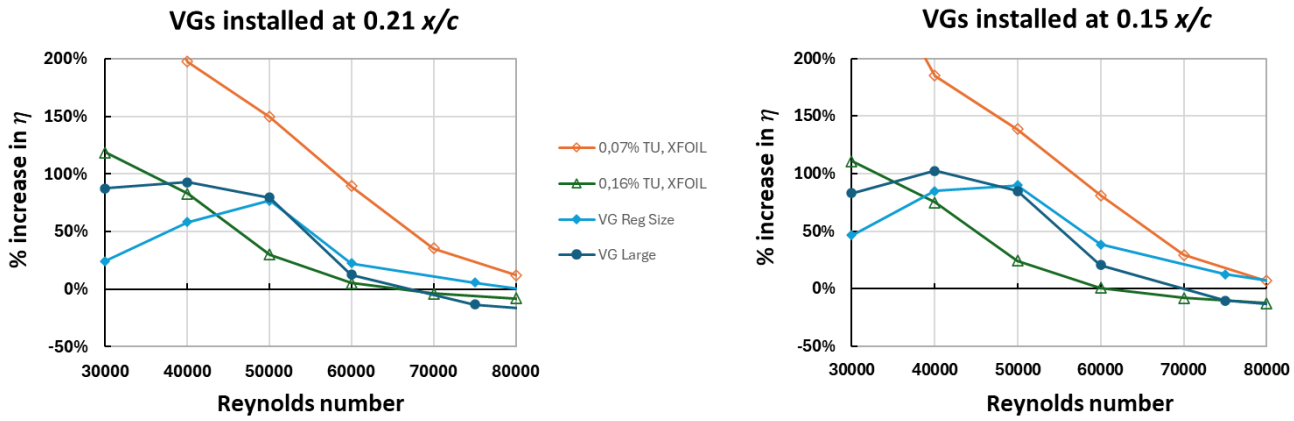


Figure 6 – Improve in aerodynamic efficiency at an angle of attack of 5°. Left: comparison between the configuration with vortex generators installed at 0.21 x/c and the results obtained with XFOIL when the transition is forced at the same chordwise position. Right: comparison between the configuration with vortex generators installed at 0.125 x/c and the corresponding XFOIL prediction with transition forced at that location.

5. Conclusions

This study experimentally investigated the aerodynamic performance of the NACA 4412 airfoil at very low Reynolds numbers, a regime usually neglected in the past in relation to the use of VGs to enhance airfoil performance. The primary objective was to avoid the formation of the LSB and mitigate its adverse effects on overall aerodynamic efficiency by means of conventional, backward-facing wishbone VGs. To determine the optimal configuration, these devices were tested at two distinct chordwise locations and sizes.

The experimental results indicate that the effectiveness of the VGs is highly dependent on the operating Reynolds number. At the lowest values (around $3–5 \times 10^4$), the baseline airfoil shows a marked degradation in lift-to-drag ratio associated with laminar separation, while appropriately sized VGs can increase aerodynamic efficiency by up to about 100%, evidencing a substantial delay of separation. As Reynolds number increases toward 1×10^5, the benefit of the VGs becomes more moderate, typically in the range of 5–10%, consistent with a progressively more robust boundary layer. Because the Reynolds numbers explored here are lower than those usually considered “low Re” in the VG literature, standard sizing based on a boundary-layer-height fraction leads to underperforming devices; doubling the VG height restores adequate momentum transfer from the outer flow and is clearly advantageous at the lowest Re, albeit at the cost of some performance loss at the highest Re in the tested range.

Because the boundary layer at these low Reynolds remains predominantly laminar over a larger portion of the chord, the appropriately sized and positioned wishbone VGs successfully increase the momentum mixing. The wishbone VGs, especially in the enlarged configuration, generate coherent counter-rotating vortices that increase momentum mixing between the outer flow and the near-wall region, postponing separation and mitigating the LSB without immediately forcing transition to a fully turbulent boundary layer along the whole chord.

The results also indicate that moving the wishbone VGs forward from $x/c = 0.21$ to $x/c = 0.15$ is beneficial across all Reynolds numbers considered. Placing the VGs at $x/c = 0.15$ provides a longer development length for the streamwise vortices before they reach the natural separation region, which enhances their capacity to energize the boundary layer and suppress or displace the laminar separation bubble.

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Open Data

The data obtained in this experimental campaign is incorporated into the repository Zenodo [8].

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