1 Introduction

Low Reynolds number aerodynamics and related boundary layer separation control have a prominent role in advanced research in last twenty years due to the increasing number of engineering applications, as those related to Micro Air Vehicles (MAV) and low size wind turbines. Among the whole set of possible flow control devices, the attention is here focused onto passive ones, due to the usually simplest manufacturing, continuous working operation and more precise computation of improvements in performances. The starting point for such investigations is the observation that aerodynamic performances are highly dependent on Reynolds number. For Reynolds numbers lower than $10^5$, there is a sharp reduction of performances of conventional wings (as for example the efficiency). On the other hand, the use of passive rough elements placed at specific positions on the wing surface allows improving the wing efficiency of one order of magnitude in comparison to a smooth wing (Lissaman, 1983). This happens for Reynolds numbers around $10^3$, i.e. just in situations encountered in previous mentioned applications.

The main source of performance degradation at low Reynolds number is the separation bubble on the wing upper surface, which increases drag and reduce lift, Radespiel (2006). The perturbing element allows delaying the separation bubble formation, so far leading to performance improvements. However, this is not obtained for every perturbing element size, shape, location and local velocity. Regarding size and local velocity, previous investigations on flat plates highlight the existence of a critical local Reynolds number, $(Re_k)$, obtained using the surface element height, $k$, and the undisturbed local velocity outside the boundary layer $(U_l)$ equal to 840 (Tani and Sato, 1956). For local Reynolds numbers lower than this value, the perturbation is not altering the main flow behavior, whereas for values over such a threshold, the flow gains enough energy to delay flow separation (Son et al., 2011). For curved surfaces, this critical number moves into the interval from 690 to 830 (Huber and Mueller, 1987). Thus for a given perturbing element size, the derived effects are basically related to the value of the local velocity, i.e. linked to the global flow Reynolds number.

Regarding the perturbing element shape, in the past, the use of three-dimensional perturbing elements as in Kerho and Bragg (1997) with semi-spheres at the leading edge of a NACA 0012 airfoil, in Lyon and Selig (1997) with single or multiple rectangular strips at different positions and in Sathanakrishnan and Jacob (2005) with regular bumps over the whole surface, leads to a reduction of the separation bubble and of pressure drag by forcing the transition from laminar to turbulent conditions.

On the other hand, the use of a small cylinder along the span, i.e. trip wires, allows Huber & Mueller (1987) to attain also a slightly increased efficiency, depending on the wire position. Such a solution, which has the advantages of being easily adaptable to the wing geometry, was reconsidered in much detail by Choi and co-workers (Son et al., 2011) emphasizing the similarities with solutions implemented in nature (biomimetics).

It is quite hard to determine theoretically the optimal position for the perturbing transition element, being this possible only for very small pressure gradient, i.e. for small angle of attack, a condition not so relevant for practical applications. Therefore, it is fundamental to exploit extended experimental and numerical investigation on specific perturbing elements. In addition, it is important to relate the improvement in wing performances to the detailed features of the separation bubbles and of the entire flow field.

The objective of the present work is to investigate the effects of small cylindrical trip wires on the aerodynamic features of a rectangular wing at Reynolds numbers between $5\times10^3$ and $2\times10^5$ (based on the wing chord) which are just below and above the critical value. Specifically, the diameter and position of the perturbing cylinders are modified to evaluate global indicators of performances as drag and lift forces, together with detailed information on the flow field around the wing, aiming to derive improvements and related explanations. The relevance of the present investigation lies in applications of such wings in wind turbines, especially those of small and intermediate scales, in Unmanned Air Vehicles (UAV) and in Micro Air Vehicles (MAV), working in the same interval of tested Reynolds numbers.
2 Experimental set-up

Measurements have been performed on a subsonic wind-tunnel with circular open cross-section (diameter equal to 1 m) in which the rectangular wing model (airfoil NACA 2412, aspect ratio ≈3) is positioned. The free stream velocity of the wind tunnel is changed to attain Reynolds numbers ($Re$, based on the wing chord, $c=133$ mm) between $5 \times 10^4$ and $2 \times 10^5$. The trip wires used are single or multiple cylinders stuck along the span with the same aperture of the wing as reported in Figure 1 at the top. The diameters of the cylinders range from 0.005 $c$ to 0.015 $c$, corresponding from 0.044 to 0.125 in terms of wing thickness, while several positions have been tested, as detailed in Figure 1 at the bottom. The Reynolds number based on the trip wire height, $Re_k$, is around 500 for the lowest Reynolds number tests and around 1400 for the largest one, i.e. just over the threshold.

Three types of measurements have been performed, global lift and drag by using a calibrated force balance, local pressure coefficients by using multi-hole pressure tabs and velocity fields over the wing by using Particle Image Velocimetry (PIV). The last employed a Nd-Yag laser (wavelength 532 nm, 200 mJ per pulse) synchronized with a cross-correlation camera, whereas tracer are provided by oil droplets (mean diameter less than 5 µm) from a Laskin nozzle operating at 1.8 atm. The illuminated part of the wing was painted with a water solution containing Rhodamine WT (as can be noticed in Figure 1 at the top), to reduce light reflections on the surface by applying a narrow band filter over the camera objective. An example of acquired images is provided in Figure 2, in which the wing has relatively low reflection light intensity levels, whereas the tracer particles show high contrast. PIV images are processed with DaVis 7.2 by LAVISION Gmbh using a multi-pass algorithm starting from interrogation windows equal to 64×64 pixel to 32×2, with overlapping 75%. About 1000 images are averaged for each condition. Typical relative errors for global force coefficients, removing the strut contribution to drag, are less than 8% at the stall for the lowest Reynolds number decreasing to less than 3% for the largest one. The errors in PIV measurements are around 1% for instantaneous field, while the statistical error on the mean fields is smaller.

3 Results: global force measurements

In this section, the measurements of global forces made by the calibrated balance will be outlined. The results obtained without any perturbing element will be used for comparison. Preliminary measurements revealed that the configurations with multiple trip wires (placed both on the upper, lower or both wing surfaces) rather than reducing drag or increasing lift, just do the opposite, so that they will not be considered in the following.

![Figure 1: The tested wing airfoil with an example of trip wire application (at the top) and positions of the trip wires tested (indicated by asterisks at the bottom). The black circles indicate the positions with best performances.](image1)

![Figure 2: An example of acquired image in PIV. Flow from left to right and illumination from the top.](image2)

Regarding the configurations with single trip wire, the first effect to be considered is that of Reynolds number within the interval $5 \times 10^4$ to $2 \times 10^5$. In Figure 3, the lift and drag coefficients and the wing efficiency are presented for the 0.0075 $c$ wire diameter placed at 10% of the chord (black circle in Figure 1). It is clear that the maximum effect in comparison to the unperturbed wing is obtained for Reynolds numbers larger than about $10^5$. In these conditions, around the stall angles, i.e. $14^\circ$÷$15^\circ$, the lift coefficient is larger and the drag is lower than the unperturbed wing. On the other hand, far from the stall the efficiency is slightly lower than for the reference wing. It is important to point out, that for such unperturbed wing there are no differences among results when the Reynolds number is changed as derived from Table 1. The stall angle is almost constant and the maximum lift coefficient is only slightly increasing with Reynolds number.
Figure 3: Lift and drag coefficients and wing efficiency vs angle of attack, measured with force balance for different Reynolds numbers for the trip wire positioned at 10% of the chord on the upper surface (size = 0.0075 c).

Table 1. Maximum lift coefficients and angles of stall for the unperturbed and trip-wire wings at the tested Reynolds numbers.

<table>
<thead>
<tr>
<th>Re</th>
<th>Unperturbed a_s (°)</th>
<th>Cl max</th>
<th>Trip Wire a_s (°)</th>
<th>Cl max</th>
</tr>
</thead>
<tbody>
<tr>
<td>50000</td>
<td>14</td>
<td>0.7870</td>
<td>14</td>
<td>0.7535</td>
</tr>
<tr>
<td>70000</td>
<td>14</td>
<td>0.7754</td>
<td>15</td>
<td>0.8893</td>
</tr>
<tr>
<td>100000</td>
<td>14</td>
<td>0.8158</td>
<td>16</td>
<td>0.8526</td>
</tr>
<tr>
<td>130000</td>
<td>14</td>
<td>0.8206</td>
<td>16</td>
<td>0.8261</td>
</tr>
<tr>
<td>150000</td>
<td>14</td>
<td>0.8168</td>
<td>16</td>
<td>0.8303</td>
</tr>
<tr>
<td>182000</td>
<td>14</td>
<td>0.8287</td>
<td>16</td>
<td>0.8261</td>
</tr>
<tr>
<td>200000</td>
<td>14</td>
<td>0.8290</td>
<td>16</td>
<td>0.8293</td>
</tr>
</tbody>
</table>

Figure 4: Maximum lift coefficient and stall angle as a function of Reynolds number for the unperturbed wing and that with trip wire positioned at 10% of the chord on the upper surface (size = 0.0075 c).

On the other hand, as also reported in Table 1, the results using the trip wire are strongly dependent on Reynolds number. Indeed, an increase in maximum lift coefficient and stall angle is noticed. The situation is better summarized in Figure 4, where maximum lift coefficient and stall angle with and without wire are compared. From this figure, it is observed that there is a remarkable increment of maximum lift with trip wire only in the interval of Reynolds numbers between $6 \times 10^4$ to $1.2 \times 10^5$, whereas the increment in stall angle with trip wire is present in the whole range $Re>5 \times 10^4$.

The attention is then focused on the effect of wire diameter at a fixed position (10% of the chord on the upper surface), leaving a fixed external Reynolds number $Re=1.5 \times 10^5$, as displayed in Figure 5. It is clearly noticed that the highest lift and stall angle are obtained for a diameter of 1 mm (0.0075 c), in comparison to the unperturbed wing and to smaller or larger diameters. Regarding the wing efficiency, it is larger for the unperturbed wing in comparison to those equipped with trip wire, while around the stall again the wing with the 1 mm wire gives the best performances with a stall delay of about 2°. Starting from the previous results, the attention is focused on such a 0.0075 c trip wire at Reynolds numbers around $10^5$, by looking at the effect of a change in the position of the wire.
Among all tested configurations, the other one which gives an improvement of performances is the one with the trip wire positioned just at the leading edge (the second black circle in Figure 1). As displayed in Figure 6, in this case, the improvements in stall angle are less remarkable (about 1°), but the stall is smoother and more regular, thus also very interesting for possible applications. In addition, far from the stall, the performances are much closer to the undisturbed wing in comparison to the wire positioned on the upper wing surface.

4 Results: velocity measurements

To investigate the motivation of these behaviors, the velocity fields on the wing were measured by PIV. In Figure 7, an example of average vector field, down-sampled to one vector over four, is presented for an angle of attack equal to 12° in the case of trip wire at 10% of the chord at Re=1.5×10^5. The increment of velocity at the upper surface in noticed as also the position of the wire element (the bump on the wing upper surface).
Figure 7: Example of mean vector field with overlapped colours of absolute velocity for the wing with trip wire at 10% of the chord on the upper surface. Angle of attack equal to 12°, Re=1.5×10^5.

The comparison among the unperturbed wing, the one with trip wire at 10% of the chord on the upper surface and that with trip wire at the leading edge for an angle of attack equal to 12° and $Re=1.5\times10^5$ (i.e. just before the stall region in Figure 5) is given in Figure 8. Even in these conditions, in which the flow is not separated whatever the geometrical configuration, it is evident that the region with maximum streamwise velocity moves upstream when trip wires are used. Specifically, while for the unperturbed wing the maximum is centered at about 0.17 c, for the wing with wire at 10% of the chord, this moves to 0.14 c and for the wing with wire at the trailing edge to less than the 0.1 c. This is a clear indication of a modification in the upper flow as also pointed out by the reduced extension of the incremented velocity region. In all three conditions, the boundary layer is not separated even just downstream the perturbing elements.

The situation changes when stall is approached. In Figure 9, the comparison among the same three configurations of Figure 8 are presented for an angle of attack equal to 15° and $Re=1.5\times10^5$ (i.e. in the stall region in Figure 5). While in the first condition, there is a large separation region, with the use of the trip wire the flow is perfectly stuck on the wing. Therefore, for the configurations with perturbing elements a delay of stall with increased maximum lift and decreased drag must be expected, as reported in global force measurements (Figures 3 to 6). In the wings equipped with trip wires, the separation is completely avoided with only a boundary layer thickening along the wing surface.

The rms of streamwise velocity has been computed and is presented in Figure 10 for the same configurations considered before. The separation on the upper surface for the unperturbed wing is characterized by a continuous mixing layer in which separating vortices are moving, whereas the near wall region has a relatively low level of turbulence.

Figure 8: Comparison of mean streamwise velocity fields for the unperturbed wing (at the top), trip wire at 10% of the chord (in the middle) and wire with trip wire at the leading edge (at the bottom). Angle of attack equal to 12°, Re=1.5×10^5.

For the wings with trip wires, turbulence fluctuations are mostly located around the perturbing element, so far leading to a higher turbulent kinetic energy of the air stream which allows overcoming the adverse pressure gradient. The related boundary layers have clearly much higher turbulence levels when developing along the wall in comparison to the undisturbed wing. The wing with trip wire just at the leading edge displays a small high turbulence region for x/c <0.1 due to a small separation.
Figure 9: Comparison of mean streamwise velocity fields for the unperturbed wing (at the top), trip wire at 10% of the chord (in the middle) and wire with trip wire at the leading edge (at the bottom). Angle of attack equal to 15°, $Re=1.5\times10^5$.

The change of the flow field around the investigated wings is also well described by the behavior of the vertical mean velocity as reported in Figure 11. The displacement towards the leading edge of the whole flow is confirmed by the movement of the positive vertical velocity region, in agreement with the observation already made for Figure 8.

Figure 10: Comparison of rms streamwise velocity fields for the unperturbed wing (at the top), trip wire at 10% of the chord (in the middle) and wire with trip wire at the leading edge (at the bottom). Angle of attack equal to 15°, $Re=1.5\times10^5$.

Therefore, the beneficial effects of trip wires are related to both a modification of the mean flow field which is moved towards the leading edge and to a simultaneous increment of turbulence fluctuations downstream the perturbing element. The former induces high velocity and low pressure levels leading to a small separation close to the leading edge.
The latter energised the external air stream and both effects allow neutralising the adverse large pressure gradient present at these angles of attack.

It has been shown in the global force measurements that the stall for the wing equipped with trip wires at 10% of the chord is quite sharp, whereas that exhibited by the wing with trip wire at the leading edge is much smoother.

To investigate the flow fields in these conditions, the post-stall angles are considered for such two wings as presented in Figure 12. For an angle of attack of 17°, the wing with trip wire at 10% of the upper surface presents a leading edge stall similar to that of the unperturbed wing, reported in Figure 9, i.e. a rather abrupt leading edge stall. On the other hand, when the trip wire is positioned just at the leading edge, the separation is less pronounced and the stall is moved downstream (trailing edge stall due to boundary layer separation) thus leading to the global force results presented in Figure 6.

It is interesting to verify that at Reynolds number around $5 \times 10^5$, for the trip wire of diameter equal to 0.0075 c, the previous effects are not observed. In Figure 13, the same plots presented in Figure 9 are given for such a small Reynolds number. It is clear that now, in contrast with the flow fields given in Figure 12, the behavior among undisturbed wing and that equipped with trip wire at 10% of the chord is very similar. They both present a large separation related to leading edge stall as also reported in force measurements (Figure 3).
5 Remarks and Conclusions

The present experimental investigations on trip wire effects consider several variables as position, size and external velocity. On the other hand, the shape is fixed to cylindrical due to the easy manufacturing and stability.

The size and velocity effects are grouped within the critical local Reynolds number which must be larger than about 700 (for a curved surface as the present one) to get beneficial effects. Indeed, the present experiments are performed at a critical Reynolds number just around this threshold. Specifically, for the smaller wire diameter, we are always below the threshold, whereas for the larger ones it is overcome at high free stream velocity. In these last conditions, the wire elements allow improving the wing performances due to a combined effect of induced larger mean velocity (and low pressures) and higher turbulent kinetic energy in comparison to the unperturbed wing.

Regarding the position of the perturbing element, it has been pointed out that when the element is placed on the wing upper surface (the optimal position for the present wing is 10% of the chord), the stall is delayed at about 17° rather than about 15°. However, it still presents similar features to that of the undisturbed wing, i.e. an abrupt stall originating from leading edge. On the other hand, when the trip wire is placed just at the leading edge, the stall is still delayed to about 16°, but it attains the characteristic features typical of trailing edge stall due to boundary layer separation which is much more gradual than the previous one.

References


Lyon C., Selig M., Broeren A. (1997), Boundary layer trips on airfoils at low Reynolds numbers, AIAA 97-0511.


Figure 13: Comparison of mean streamwise velocity fields for the unperturbed wing (at the top) and trip wire at 10% of the chord (at the bottom). Angle of attack equal to 15°, Re=5×10^6.