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On the Use of Gurney Flaps for the Aerodynamic Performance Augmentation of Darrieus Wind Turbines

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Abstract

Gurney Flaps (GFs) can enhance the aerodynamic performance of airfoils, making them generate more lift and delaying the onset of stall. Since their potential was discovered in the early '70s, GFs have been applied in several fields, including wind turbines. Here, the research has been focused mostly on the use of GFs in Horizontal Axis Wind Turbines (HAWTs), whereas a lack of studies involving the application of these devices on Darrieus Vertical-Axis Wind Turbines (VAWTs) is apparent in the literature. The benefits induced by GFs could actually be particularly interesting for this type of wind turbines, which are presently receiving a renewed attention from the industry.

In the present work, an extended numerical analysis using Computational Fluid Dynamics (CFD) was carried out with the aim of evaluating the potential of using Gurney Flaps for the power augmentation of Darrieus wind turbines.

After a validation of the numerical approach using wind tunnel experimental data on a static airfoil, the simulations have assessed the impact of different GF mounting and height on board airfoils moving in the cycloidal motion typical of Darrieus wind turbines. The results on a single rotating airfoil allowed the analysis to highlight the physical phenomena taking place past the rotating blades, including the delay of stall and the modifications induced on the surrounding flow field; power enhancement higher than 20% were shown for some configurations. Then, impact of GFs on a real three-blade turbine was analysed. The best configuration resulted in a 2% GF installed in the inner side of the airfoil, so to have a better torque extraction in the downwind half of the revolution. The GF benefits were apparent especially at lower tip-speed ratios, suggesting its use both for newly-designed turbines and even as a retrofitting solution in existing rotors.

Keywords: Darrieus, wind turbine, Gurney Flaps, CFD, power augmentation, flow control

1. Introduction

1.1 Background

The increasing interest in deep-water floating applications and on wind turbine installations in turbulent flows, is putting vertical-axis wind turbines back again in research agendas [1]. Even if

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36 horizontal-axis turbines are still by far the most exploited solution, in the two aforementioned fields
37 of application the Darrieus concept seems to offer some undisputed advantages, like the more
38 favorable structural loads, the insensitivity of these rotors on changes in wind direction, misaligned
39 flows or turbulence [2]. Moreover, it should be remembered that the Darrieus concept is intrinsically
40 very suitable also for tidal current applications, where the higher fluid density allows a reduction of
41 the revolution speed, while keeping the advantages of the Darrieus concept in terms of omni-
42 directionality [3-4].

43 However, the overall energy conversion efficiency of these machines is still lower than that of
44 horizontal-axis ones [5]. To partially fill this gap, innovative aerodynamic solutions are being studied
45 (e.g. [6-7]), together with a continuous research into a deeper understanding of the physics involved
46 in these rotors functioning and of the influence of the operating parameters [8-10]. Another possible
47 way of enhancing the performance of Darrieus rotors could be represented by passive or active flow
48 control devices to be applied on the airfoils [11]. Inter alia, Gurney Flaps (GFs) are one of the most
49 attractive solutions.

50 Gurney Flaps are simple devices consisting in small tabs that can be applied perpendicularly to
51 the trailing edge of airfoils, on their pressure side, to increase their aerodynamic performance. They
52 were firstly implemented in the early '70s on the rear spoilers of F1 vehicles by the US driver Dan
53 Gurney, who experienced an increase of the downforce thanks to these devices. Later, Liebeck [12]
54 conducted a systematic experimental campaign on a Newman airfoil (a wedge-shaped airfoil with an
55 elliptical leading edge), actually confirming that GFs could enhance the lift force of airfoils. He also
56 suggested that GF height should be kept below 2% c to maximize the aerodynamic benefits, which
57 would be otherwise nullified by a noticeable increase in drag. In his study, Liebeck assumed that the
58 flow field around the airfoil underwent a change that could be theoretically described by the picture
59 reported in Figure 1, where a comparison with the flow over the smooth airfoil is also shown.

60 This change basically consists in the formation of a stagnation zone upstream of the GF, i.e. a
61 separation bubble characterized by an adverse pressure gradient, and a couple of counter-rotating
62 vortices downstream the GF. Many studies [13-20] later confirmed the presence of this characteristic
63 vorticity, pointing out that it was responsible for an increase of suction on the airfoil upper surface
64 and of pressure on its lower surface, and accordingly for a substantial increase in the lift coefficient.
65 Furthermore, it was found that the aft-loading of the airfoil was augmented and the flow was pushed
66 downwards after it lefts the trailing edge. The same works also highlighted that the stall was achieved
67 at a lower angle of attack in comparison with the baseline smooth airfoil, and the zero-lift angle of
68 attack became more and more negative as the GF height was increased, suggesting that the effective
69 camber of the airfoil was augmented. Lastly, as remarked by several other works [21-24], the
70 deployment of GFs involved also the presence of a von Karman vortex street of alternately shed
71 vortices in the wake of the airfoil.

72 As one can easily imagine, the effects linked to the use of GFs strongly depend on their
73 configuration, i.e. their geometrical features as well as their mounting details. Among them, the height
74 of the GF is surely one of the pivotal parameters, since the lift enhancing effect of the flap is
75 strengthened as soon as its height is increased. At the same time, the drag force is likewise
76 emphasized, such that its magnitude could nullify the GF benefits if a certain threshold of the flap
77 height is exceeded.

78 Accordingly, many authors [19,25,26] concur with the fact that the GF size should be kept below
79 the boundary layer thickness measured at the trailing edge on the pressure side of the airfoil, in order
80 to obtain a beneficial lift-to-drag ratio.

81 **1.2 Aim and methods**

82 The GF has proven to have interesting implications in a wide range of fields. The work by Wang
83 et al. [27], as well as that of Troolin [23], indeed provides an extensive overview of the GF
84 applications, which include both low and high-speed airfoils [28], aircrafts, wings, helicopter rotors
85 [29] and, recently, wind turbines. Focusing on this latter application, many literature instances suggest

86 the GF as a promising device not only for active flow control [30-35], but also for turbine performance
87 increase [36-38]. Notwithstanding this, it's worth remarking that all the aforementioned works coped
88 with the application of GF on HAWTs, whereas the lack of studies concerning the deployment of this
89 device on VAWTs was apparent. Only a few papers were indeed found addressing specifically this
90 issue [39-41], even though the analyses are often based on lumped aerodynamic coefficients,
91 discarding several unsteady aerodynamic phenomena, which are however of capital relevance for a
92 correct description of the GF effects.

93 The present work thereby is aimed at investigating the effects of GFs on the performance of a
94 Darrieus wind turbine by means of 2D unsteady CFD simulations. In particular, both low (left-hand
95 side of the power coefficient curve) and high (right-hand side of the power coefficient curve) tip-
96 speed ratio (TSR – Eq. 1, where Ω is the revolution speed of the turbine of radius R and U is
97 undisturbed wind speed) were studied. Different GF sizes and mounting configurations were also
98 tested.

$$TSR = \frac{\Omega \cdot R}{U} \quad (1)$$

99 The study is organized as follows. A detailed presentation of the numerical approaches used in
100 the study is first presented in Section 2, together with the selected study cases. Indeed, a literature
101 case study concerning the use of GFs on a static airfoil was first selected, with the purpose of
102 validating the selected CFD setup by means of experimental findings. The selected case study
103 presented the static polars of a NACA0011 airfoil [15], with and without GFs, obtained with wind
104 tunnel tests. The effects of mounting GFs on a Darrieus turbine were then investigated using both a
105 single NACA0021 airfoil in cycloidal motion and a full turbine featuring the same airfoils. The results
106 related to all these airfoils are reported in Section 3. The results are finally discussed.

107 **2. Methodology**

108 **2.1 CFD validation**

109 Before going into the actual investigation about the effects of GF on the Darrieus turbine, a
110 validation of the numerical model used in the following calculations was carried out. In particular,
111 the aim of the study presented in this section, was to verify that CFD was able to predict the trend of
112 the airfoil static polars effectively. If in fact, the approach was proved to be very predictive in case of
113 conventional smooth airfoils [42], its suitability also for those equipped with GFs had to be verified.
114 To this end, the study from Myose et al. [15] was here considered. The authors of [15] performed
115 experimental tests on a NACA0011 airfoil in the Wichita State University Beech memorial low speed
116 wind tunnel. For the purpose of the present study, the data sets corresponding to the smooth airfoil
117 and to GF heights of 1% c and 2% c were considered, since they were fully comparable with the values
118 that will be taken into account in the present study. In the paper, the authors published raw data
119 directly from experiments, but gave full details about the wind tunnel and the experimental setup. In
120 order to compare the results with CFD simulation in an open domain, experimental data were then
121 corrected using the classical expressions for solid blockage and wake blockage into a nearly two-
122 dimensional domain reported in [43].

123 **2.2 Case study and test plan**

124 In order to address the analysis of the GF effect on the Darrieus VAWTs, a case study was first
125 selected. Namely, the 2D model used in CFD calculations was extrapolated from the turbine which
126 has been tested recently in the wind tunnel of the Politecnico di Milano (Italy) by Dossena et al. [44].

127 The same rotor, whose main geometrical features are listed in Table 1, was also exploited in several
128 works by Balduzzi et al., by means of both 2D [45-47] and 3D [48,49] CFD simulations.

129 In particular, most of previous works were focused on the rotational regime corresponding to
130 $TSR=3.3$, since it was deemed to be particularly interesting within the whole functioning range of the
131 turbine. On one hand, this condition is characterized by a fairly high power coefficient (near to the
132 peak of the power curve) and thus it represents a possible working condition for the rotor; on the other
133 hand, it involves several complex aerodynamic phenomena, including stall, because of the relatively
134 large variation of the incidence angle occurring during a revolution, and thus it poses remarkable
135 challenges in terms of CFD study. Based on this significant amount of past numerical experience
136 concerning the regime of $TSR=3.3$, this functioning condition was selected as the starting point for
137 the present investigation.

138 According to [50-52], it was also decided not to immediately simulate the complete three-blade
139 rotor, but to initially reproduce a one-blade study turbine having the exact features of the one reported
140 in Table 1. This decision was based both on physical considerations and on hardware limitations. On
141 one side, this strategy indeed allowed the authors to isolate the aerodynamic effect of GFs from the
142 complicated aerodynamic phenomena involved by multiple blade/wake interactions occurring in a
143 real multi-blade rotor. On the other side, from a more practical viewpoint, it also made it possible to
144 mitigate the computational burden associated with the simulations: the need of providing a proper
145 level of spatial refinement in proximity of the blade, would indeed have required a grid with more
146 than 1.5 million elements for a three-blade rotor, which would have taken too much time and exceeded
147 the resources available for the present study. Accordingly, the more affordable computational burden
148 made possible to perform several sensitivity analyses, as better clarified below.

149 In summary, the analysis was developed through three main conceptual steps, detailed below:

150 1. *Assessment of GF effects on NACA0021 static polars*

151 The suitability of the numerical approach in replicating the aerodynamic effect of GFs was
152 first assessed on the static NACA0021, being this the airfoil mounted on the case study
153 rotor; in particular, due to the lack of literature studies concerning the GF effects on this
154 specific airfoil, the static polars using a 2% GF were calculated and compared to those of
155 the smooth airfoil.

156 2. *GF effects on a single NACA0021 airfoil in Darrieus motion*

157 The functioning point corresponding to $TSR=3.3$ was studied and a first sensitivity
158 analysis was carried out against different configurations of the GF, keeping its height fixed
159 at a value of 2% (corresponding to approximately 1.7 mm for the present case study).
160 More in detail, the following configurations of the GF, which differed each other according
161 to the side of the blade where the GF was mounted (see Figure 2), were simulated and
162 compared:

- 163 ▪ *Baseline smooth* configuration: baseline airfoil with no GF;
- 164 ▪ *GF_{in}* configuration: flap mounted on the inner side of the airfoil, that is, the one
165 facing the axis of rotation of the turbine;
- 166 ▪ *GF_{out}* configuration: flap mounted on the blade's outer side, that is, the one facing
167 the boundaries of the computational domain;
- 168 ▪ *GF_{both}* configuration: flap mounted on both sides of the airfoil.

169 The reasons why these three different options were chosen for the GF, as well as the
170 corresponding expected outcomes in terms of performance for the wind turbine, will be
171 better clarified in Section 3.3.

172 A sensitivity analysis on different heights of the GF (h_{GF}) was then carried out, in order
173 to assess which size would have been more valuable for the simulations at other TSRs.

Hence, in addition to the previously investigated 2%*c* height, also 3%*c* (≈ 2.6 mm) and 4%*c* (≈ 3.4 mm) sizes were simulated. Finally, the analysis was extended to other functioning points of the hypothetical one-blade rotor, i.e. TSR=2.4, TSR=3.9, TSR=4.5 and TSR=6.0. For each of these values, the size of the GF was kept at 2%*c*, whereas its mounting configuration was varied within the ones reported above.

3. *GF effects on the full three-blade case-study Darrieus turbine*

The final part of the present study coped with the full three-blade rotor of Table 1. By doing so, the impact of the mutual interaction between the blades could be accounted for. Given the significantly higher computational burden involved, only one GF height was tested (namely, the 3%*c* GF). The reasons that made the authors select this GF size will be better explained in Section 3.6. The power coefficients at different TSRs were calculated for each of the previous GF configurations, and the power curve associated with each of them was obtained.

2.3 Numerical CFD approach

The computational domains adopted for the CFD simulations are reported in Figure 3. In case of the NACA0011 static polars used for the CFD validation (calculated at $Re = 2.2 \times 10^6$, i.e. the same value declared by the study by Myose et al. [15]), as well as those used for the first preliminary assessment of the GF effect on the NACA0021 static airfoil (calculated at $Re = 1.5 \times 10^5$), the domain was made of the conventional bullet shape (Figure 3(A)), featuring an overall widening angle of 50 deg and distances of 34 and 40 chords upstream and downstream of the airfoil, respectively. The choice of the bullet-shape domain in case of static polars is due to the chance given by this shape of investigating the whole set of angle of attack (AoA) simply modifying the flow angle at the inlet, while keeping the computational grid fixed. To avoid any recirculation in the inlet boundary, of course the maximum AoA is that corresponding to the inclination of the lateral sides of the domain itself. The dimensions of the bullet, were in agreement with the most conservative suggestions that can be found in the literature.

As regards the simulations of the single rotating airfoil, as well as the full three-blade rotor, the sliding mesh technique was employed [53-55]. The physical domain was then split into two subdomains (Figure 3(B)), i.e. a circular zone containing the airfoil, rotating with the same angular velocity of the rotor, and a rectangular fixed outer zone, determining the overall domain extent. In this case, the inlet velocity is always normal to the boundary, then the bullet-shaped domain is not appropriate anymore. The overall characteristics of the computational domain are in agreement with the prescriptions of [55]. Given the purpose of this analysis, only the airfoil was taken into account, neglecting the presence of the spoke and the shaft. According to the sensitivity analyses on this kind of study cases reported in [45-47], a velocity-inlet boundary condition was imposed at the inlet section, which was placed 40 rotor diameters upwind from the rotating axis. To reproduce the experimental data of [44], the inlet wind velocity was set to 9 m/s. The ambient pressure condition was imposed at the outlet boundary, 100 rotor diameters downwind, while a symmetry condition was defined on lateral boundaries, placed at a distance of 30 rotor diameters. The stationary and rotating regions communicate with each other by means of a sliding interface condition [54].

The works by Balduzzi et al. [51,55] were taken as the main references in order to select the most suitable numerical settings for the solver. For the sake of completeness, however, a brief overview on the main settings of the simulation models is given below.

The commercial code ANSYS® FLUENT® [56] was used in the two-dimensional form to solve the time-dependent unsteady Reynolds-Averaged Navier–Stokes (U-RANS) equations in a pressure-based formulation. The fluid was air, modeled as an ideal compressible gas with standard ambient conditions, i.e. a pressure of 1.01×10^5 Pa and a temperature of 300 K. Based on the comparative

222 analyses of [55], the turbulence closure was achieved by means of Menter's Shear Stress Transport
 223 (SST) model [57], which is derived from the $k-\omega$ two-equation formulation and coupled with the
 224 Enhanced Wall Treatment for the computation of the boundary layer in the near-wall regions. The
 225 *Coupled* algorithm was employed to handle the pressure-velocity coupling. The second order upwind
 226 scheme was used for the spatial discretization of the whole set of RANS and turbulence equations, as
 227 well as the bounded second order for time differencing to obtain a good resolution.

228 As regards the static polars, the achievement of convergence was assessed verifying that the
 229 difference between two consecutive computed values of the lift and drag coefficients (Eq. 2, where ρ
 230 is the air density, S the blade area, W the relative speed, F_L and F_D are the lift and drag forces,
 231 respectively) remained constantly below a threshold level of 0.1%:

$$c_L = \frac{F_L}{0.5 \cdot \rho \cdot S \cdot W^2} \quad c_D = \frac{F_D}{0.5 \cdot \rho \cdot S \cdot W^2} \quad (2)$$

232 As regards the rotating airfoil, as well as the full three-blade turbine, the global convergence of
 233 each simulation was monitored by considering the difference between the mean values of the torque
 234 coefficient (Eq. 3, where A is the turbine front area, U is the absolute wind velocity and R is the
 235 turbine radius) over two subsequent revolutions. The periodicity error threshold was set to 0.1%:

$$c_T = \frac{2 \cdot \text{torque}}{\rho \cdot A \cdot U^2 \cdot R} \quad (3)$$

236 The meshes generated for the two domains were of unstructured type. Triangular elements were
 237 used for the discretization of the core flow region, whereas a structured O-grid was created around
 238 the airfoils to accurately resolve the boundary layer.

239 The first element height was always chosen so as to guarantee that the y^+ values at the grid nodes
 240 of the first layer above the blade wall did not exceed the limit of the SST turbulence model, i.e. $y^+ \sim$
 241 1. The expansion ratio for the growth of elements starting from the surface was kept below 1.05 to
 242 achieve good mesh quality. The airfoil surface was discretized with a number of nodes which varied
 243 between 1000 and 2300, depending on the shape of the simulated airfoil (either NACA0011 or
 244 NACA0021), as well as the size of the GF and its configuration.

245 Proper mesh sensitivity studies were performed for all the study cases. In case of the static polars
 246 for both the NACA0011 and the NACA0021 (in case of both the smooth airfoils and the one with
 247 GFs), three computational grids were generated by varying the number of nodes on the airfoil surface
 248 and the refinement level applied into the wake zone downstream of the GF. The three meshes were
 249 featuring a total grid size of approximately 2.3×10^5 , 4.3×10^5 and 8.8×10^5 elements, respectively. It
 250 was found a difference between the lift coefficients predicted by the two most refined meshes
 251 constantly lower than 1%. In case of rotating airfoils, the meshes were verified by proper mesh
 252 sensitivity studies in [48,49]. In case of the use of GFs, the same maximum level of refinement used
 253 for the static case for the NACA0021 was used. Overall, it was verified after the simulations that the
 254 meshes for the rotating airfoils were able to fulfill the requirements in terms of limiting the
 255 dimensionless vorticity proposed by Balduzzi et al. [51]. Figure 4 shows some details of the
 256 computational grid used for the simulations of the rotating airfoil, with particular focus on the
 257 refinement zones used to properly discretize the leading and trailing edges of the airfoil and its wake.
 258 As an example, the *GFboth* configuration is reported there.

259 Regarding the temporal discretization, the static polars were calculated using a steady RANS
 260 approach up to the static stall angle, while after that the method was switched to a U-RANS one, with
 261 a timestep of 5×10^{-4} s and 2×10^{-3} s for the NACA0011 and the NACA0021, respectively. In case of the
 262 rotating blade, as well as the complete rotor, additional care in comparison to conventional Darrieus
 263 simulations was requested by the selection of the angular spacing between two consecutive timesteps
 264 (angular timestep). Firstly, this had to be proportionally adapted to the revolution speed of the rotor,
 265 i.e. it had to be reduced for small TSRs, in order to match the requirements in terms of limiting the

266 Courant number in proximity of the blades as proposed by Balduzzi et al. [51,55]. Moreover, in the
267 present application, the presence of the shedding vortices generated by the flow over the GF could
268 not be disregarded, because a too coarse temporal discretization could prevent the phenomenon itself
269 from being detected.

270 Accordingly, the pressure fluctuations associated with the shedding would not be captured by the
271 CFD and this could potentially lead to a wrong prediction of the torque and power curves.
272 Consequently, a maximum threshold for the value of the angular timestep was established in order to
273 ensure that at least 10 points per shedding cycle were captured by the simulations. More in detail, the
274 angular sector corresponding to a shedding cycle was calculated by Eq. 4, where f_s was the expected
275 shedding frequency and was evaluated in Eq. 5, according to the definition of the Strouhal number
276 (St).

$$\Delta \vartheta_s = \frac{\Omega}{f_s} \frac{180}{\pi} \quad (4)$$

$$f_s = St \frac{W_{\max}}{h_{GF}} \quad (5)$$

277 In the previous equation, $W_{\max} = (U^2 + \Omega R^2)^{0.5}$ is the highest relative velocity experienced by the
278 airfoil and h_{GF} is assumed to be the characteristic length governing the shedding development. After
279 each simulation, the consistency of the selected timestep was verified using the actual shedding
280 frequency detected by the simulations. As a result, timestep sizes ranging between 0.08 deg and 0.72
281 deg were used. The size of the different computational grids and the calculations cost are reported in
282 Table 2.

283 As a final remark on the numerical CFD approach, it is worth pointing out that, in spite of the
284 increase of the computational cost, the authors decided to simulate even the single airfoil in a real
285 cycloidal motion (i.e. with the blade rotating physically in a straight flow field), rather than in an
286 equivalent pitching motion, in order not to discard the mutual interaction between the blades (e.g. due
287 to vortices detached upwind and convected by the flow). Moreover, this allowed also to account for
288 the AoA variation downwind due to the reduced wind speed.

289 **3. Results and discussion**

290 **3.1 Validation**

291 The comparison between the experimental polars of the NACA0011 obtained experimentally by
292 Myose et al. [15] and those resulted from the CFD simulations of the present study is reported in
293 Figure 5. Impressive agreement was found between the two data sets. The behavior of the smooth
294 NACA0011 airfoil was perfectly described by CFD, which also captured exactly the static stall angle.
295 A very slight overestimation of the post-stall lift (and under-estimation of the post-stall drag) was
296 only noticed. Most of all, CFD simulations were able to correctly reproduce the effect of the Gurney
297 Flaps, both for the 1% and the 2% chord height. The only minor discrepancy was a less abrupt stall
298 for the 2%c case. Overall, the agreement was considered fully satisfactory, thus corroborating the
299 suitability of the CFD approach.

300 **3.2 Preliminary assessment of GF effects on NACA0021 static polars**

301 Figure 6 reports the calculated lift and drag coefficients of the NACA0021, both for the baseline
302 smooth and the *GF* configurations. For the latter, a h_{GF} of 2%c was selected.

303 Please note that, due to the complicated flow structures originated in correspondence to the GF,
304 the simulations of this configuration required a much more refined angular discretization of the polar
305 with respect to the smooth airfoil; markers for the GF curve were not reported for readability. The
306 results were in good agreement with expectations. In particular, an enhancement is apparent in the
307 lift curve of the NACA0021 with the GF, whose peak value was increased by 58% in comparison
308 with the baseline configuration. The angle of attack corresponding to this peak turns out to be mildly
309 affected by the GF, having a value of roughly 12° in both cases. The effective camber augmentation
310 is likewise apparent from Figure 6, since a positive C_L is obtained for the zero incidence in case of
311 the NACA0021 with the flap. It is also interesting to note that the lift-enhancing effect of the GF
312 increases as the AoA is raised within the pre-stall region, leading to a steeper trend for the modified
313 airfoil. The stall occurs right after the highest C_L for the smooth airfoil, i.e. at an AoA of 13° . A small
314 decrease of the C_L is instead clearly outlined for the airfoil with the GF up to 15° , where a narrow
315 zone of instability anticipates the abrupt onset of stall at an AoA of 16° . According to [19], this kind
316 of stall may be induced by a sudden leading-edge bubble burst, rather than a progressive separation
317 starting from the rear region of the airfoil. Besides, the stall of the airfoil with the GF is coupled with
318 a sharp rise of the C_D , which - as expected - is higher than that of the smooth airfoil, particularly after
319 the arising of stall.

320 3.3 Sensitivity analysis on the GF configuration

321 Some preliminary considerations can be made on the effects achievable by adding the GF with
322 different configurations on the airfoil, simply based on the study of the velocity triangles obtained
323 during revolution of the turbine. According to the inherent functioning principle of the Darrieus
324 turbine, each side of the blade acts alternatively as pressure side (PS) or suction side (SS), depending
325 on whether the blade itself is passing through the upwind or the downwind zone. Namely, the outer
326 side of the blade acts as PS in the upwind half of the revolution, whereas it acts as SS in the downwind
327 one. Conversely, the opposite happens for the inner side of the blade. Provided that the GF exhibits
328 its benefits within a restricted range of positive incidence angles, its effects might be expected to be
329 favorable only within narrow portions of the revolution, whereas they might be mild, or even
330 detrimental, within others. Broadly speaking, the *GF_{in}* and *GF_{out}* configurations were likely to
331 enhance the lift on the airfoil, and hence the power extraction, only within the downwind and the
332 upwind zone, respectively, i.e. where the relative velocity incidence and the GF position matched
333 favorably. On the other hand, the *GF_{both}* configuration was expected to give an overall in-between
334 result, since reasonably it would have taken the benefits of both the cases above, introducing however
335 a higher drag force due to the larger size of the flap. These theoretical expectations were confirmed
336 by the results at TSR=3.3 of Figure 7, where the torque coefficient profiles for each configuration are
337 reported.

338 As expected, when the GF is mounted on the inner side of the blade, it provides approximately
339 the same energy extraction of the smooth airfoil in the upwind zone, whereas it significantly enhances
340 the torque in the downwind one, leading to an increase of $c_{T,ave}$ of 23.3% in comparison with the
341 baseline smooth configuration. On the other hand, when the GF is located on the outer side of the
342 airfoil, it leads great benefit in the upwind zone, while the performances in the downwind zone are
343 mildly worsened in comparison to the baseline configuration. The increase of the $c_{T,ave}$ is of 23.6% in
344 this case, i.e. very close to the value associated with the previous situation: interestingly, the
345 enhancement led by the *GF_{in}* configuration within the downwind zone and the one provided by the
346 *GF_{out}* configuration in the upwind region are of the same order of magnitude, resulting in basically
347 the same energy extraction even if this is obtained with completely different torque profiles over the
348 revolution.

349 Focusing now on the *GF_{both}* configuration, it is apparent that the envisaged outcomes were
350 correct in this case, too. In particular, the resulting torque profile is affected by both the advantages
351 and disadvantages of both the *GF_{in}* and *GF_{out}* configurations. This is proven by the fact that its trend
352 seems to be reasonably well predictable on the basis of the torque profile of the baseline smooth

353 airfoil, adding up to it the positive or negative contributions deriving by both the GF_{in} and the GF_{out}
354 configurations, for each of the azimuthal positions. Notwithstanding this, it is also apparent that the
355 final profile may be affected by other non-linear effects which clearly make the actual result deflect
356 from this mere algebra procedure. However, what matters is that apparently the advantages overcome
357 the disadvantages, resulting in a 35.3% increase in the $c_{T,ave}$.

358 3.4 Sensitivity analysis on the GF height

359 In order to contain the calculation burden, only one GF configuration was selected for the
360 sensitivity analysis on h_{GF} . Namely, provided that the GF_{both} configuration was showed to guarantee
361 the best results through the previous Section 3.3, it was deemed to be also the most reasonable choice
362 for the investigation described below.

363 From a perusal of Figure 8, where the torque profiles obtained for different h_{GF} are reported, some
364 observations can be done. First, increasing h_{GF} from 2%c to 3%c did not bring any additional
365 performance improvement in terms of average torque over a revolution: the $c_{T,ave}$ increases by 35.7%
366 in comparison with the baseline smooth air-foil, which is basically the same value provided by the
367 2%c flap. Apparently, although a slight growth of the torque is noticeable for ϑ ranging approximately
368 from 75° to 180° , this is then nullified by the mildly poorer performance occurring in the whole
369 downwind region, as well as within the first 70° sector of the upwind half of the revolution. Second,
370 it's readily apparent that a further increment of h_{GF} from 3%c to 4%c is totally detrimental for the
371 performance of the turbine. In fact, besides the fact that the $c_{T,ave}$ is mildly worsened in comparison
372 with the smooth airfoil (-5.7%), a large portion of the revolution is clearly affected by pretty strong
373 oscillations of the torque coefficient: this is distinctly an indication of the presence of shedding
374 vortices within the flow field interacting with the blade. These fluctuations seem to onset for a ϑ
375 between 270° and 300° , and they persist until the blade reaches the 90° position, achieving their
376 highest amplitude between 0° and 20° - 30° . The energy extraction of the turbine is seriously penalized
377 by this phenomenon, which gives rise to a steep drop of the torque coefficient since the very beginning
378 of the shedding, leading the c_T to become even negative from approximately 325° to 45° . One may
379 question why the shedding arises precisely when the 4%c flap is mounted on the blade, whereas no
380 such issue was found for the 2%c and the 3%c flaps.

381 This can be explained taking into consideration the physics underlying the functioning of the
382 Darrieus turbines: the larger the upwind torque extraction, the lower the energy content within the
383 downwind flow, which results in a smaller absolute wind speed acting on the blade in that region and
384 hence in a smaller incidence of the relative velocity on the airfoil.

385 In this specific case, a smaller angle of attack of the flow over the airfoil with the GF is deemed
386 to further promote the shedding, since the flow tends to interact more and more perpendicularly
387 towards the flap itself as the incidence tends to zero. Accordingly, the 4%c GF, providing the highest
388 peak torque within the upwind region among the investigated h_{GF} , is therefore deemed to lead to the
389 most conducive situation in terms of shedding promotion. Conversely, the 2%c and 3%c flaps involve
390 a smaller upwind energy extraction, resulting in a downwind incidence which is high enough to
391 prevent shedding developing: the flow is indeed assumed to generate a thicker boundary layer or even
392 separate on the suction side of the airfoil, leading to an asymmetrical interaction with the GF and thus
393 hampering the generation of organized vortex structures.

394 Finally, it is interesting to note that the increase of h_{GF} produces two effects: first, the torque peak
395 becomes higher, and second, it is achieved later during the revolution. This is likely due to the
396 combination of different factors. On one hand, the lift enhancement effect of the GF becomes stronger
397 as its height is increased, thereby the blade is capable of extracting additional energy even for
398 incidence conditions which would already become unfavorable for the baseline smooth airfoil.
399 Namely, the torque coefficient begins to decrease just after $\vartheta \approx 87.8^\circ$ for the latter, whereas it is still
400 increasing there for the GF-airfoils: in particular, the peak c_T of the 4%c airfoil is achieved for an
401 azimuthal position of $\vartheta \approx 94.4^\circ$. On the other hand, as the h_{GF} is increased, so does the drag force, and
402 this is particularly apparent in the first 30° range of the upwind region: here, the flow incidence is

almost null, hence the GF has the only effect of exacerbating the drag force, leading to a poor performance. Accordingly, the beginning of positive torque production is delayed, shifting the whole trend to the right. This is especially noticeable for the 4% case, for which the situation is further worsened by the presence of shedding, as discussed above. In fact, despite of the highest slope of this curve, due to the greatest boost action of the GF, the torque turns positive only after $\vartheta \approx 45$ deg. Subsequently, it quickly achieves its top value and then it cannot be any longer risen, since the airfoil has already reached an adverse azimuthal position, where the enhancing effect of the GF cannot outweigh the fact that the airfoil begins to stall, no matter of how long the GF itself is.

3.5 Sensitivity analysis on TSR and power curves prediction

Figure 9 reports the power coefficient (Eq. 6) of the various GF configurations as a function of the TSR; the reference power curve for the hypothetical 1-blade turbine provided by [49] and based on a state-of-the-art, free-wake, lifting-line method embedded in open source code QBlade [58] is also displayed as a reference. The importance of analyzing multiple TSRs is due to the fact that the operating conditions (in terms of AoA range and rate of variation during a revolution) deriving from these TSRs are notably different, thus allowing an in depth assessment of the aerodynamic impact of GFs under such variable conditions.

$$c_p = \frac{\text{power}}{0.5 \cdot \rho \cdot A \cdot U^3} \quad (6)$$

Focusing on the results obtained for TSR=3.3 (functioning condition near to the peak, but still in the lift-hand side of the curve, where stall is like to happen), it is readily noticeable that the values of the c_p reflect the observations reported in Section 3.3. The percentage c_p enhancements of each GF configuration in comparison with the baseline are logically the same values therein reported in terms of $c_{T,ave}$. For the reasons explained in Section 3.3, the highest performance improvement in comparison with the baseline case is provided by the *GFboth* configuration, whereas the *GFin* and *GFout* arrangements turn out to be equivalent to each other.

A similar situation is observable at the lowest simulated regime of TSR=2.4, the *GFboth* deployment still proving to be the most effective solution with a 62.5% enhancement of the c_p . Again, the *GFin* and *GFout* arrangements are represented by almost superimposed points, which namely correspond to a 31.3% and 39.1% raise of the c_p . The larger impact of GFs at this TSR can be related to the fact that the AoA range at this TSR is wider than that at TSR=3.3, magnifying the benefits offered by GF in increasing the maximum lift and delaying stall. In particular, a delay of stall in the upwind region at low TSRs is expected to modify remarkably the onset of dynamic stall [48].

Moving forward to TSR=3.9 (i.e. the curve peak, with smaller AoA variation), it is apparent that this regime roughly maximizes the performance of all the three GF configurations. To be more specific, the *GFboth* arrangement seems to show already a very slight decreasing trend, hence its actual peak value may reasonably be assumed to occur just below the TSR=3.9. Conversely, the CFD points corresponding to the *GFin* and *GFout* deployments look to have matched the peak value more accurately. It is curious that the *GFboth* and *GFout* arrangements led in this case to the same 17.3% increment of the averaged power coefficient, which turned out to be 0.370. The *GFin* configuration provides instead $c_{p,ave}$ of 0.360, which raised by 14.6% in comparison with the smooth airfoil.

Another interesting issue occurs at TSR=4.5 (i.e. a condition with an even narrower AoA range), where the *GFboth* configuration shows a notably decreasing slope and it results in the exact power extraction provided also by the baseline smooth airfoil. By the way, this functioning point can be regarded as the one which maximizes the performance of the smooth airfoil, with a $c_{p,ave}$ of 0.328. As regards the *GFin* and *GFout* configurations, they tend to give more or less the same c_p , which is increased by 8% and 10% in the two cases, respectively.

As regards the regime of TSR=6.0, the most evident fact is that the *GFboth* configuration makes the c_p dramatically drop down to a negative value, which implies that the turbine is producing a

449 resistant torque there, rather than extracting energy from the wind: this case is indeed characterized
450 by a 122.5% lower c_P in comparison with the smooth airfoil. On the other hand, the GF_{in} and GF_{out}
451 configurations still keep ensuring higher efficiency than the baseline case, leading to an enhancement
452 of the c_P of 24% and 20%, respectively.

453 In summary, two main issues arise from the considerations above. The first is that the deployment
454 of the GF on the turbine has the effect of shifting its peak power extraction capability backwards to
455 lower TSRs, in comparison with the case where the baseline smooth airfoil is used. Secondly, among
456 the examined GF configurations, the one featuring the flap mounted on both sides of the blade showed
457 its highest effectiveness at the lowest simulated TSRs, whereas its performance was massively
458 worsened at high TSRs. On the other hand, the GF_{in} and GF_{out} arrangements brought slightly poorer
459 performance at low TSRs, but constantly provided a better behaviour when compared with the
460 baseline smooth airfoil, including the high-TSR regimes where the GF_{both} configuration was proven
461 to be totally detrimental. Accordingly, this different behaviour turned out to draw up an overall flatter
462 power curve in comparison with the GF_{both} case, which instead would give rise to a very steep trend.
463 Such a selective functioning curve would involve serious handling problems within the rotational
464 speed control, eventually making the rotor less cost-attractive.

465 To understand better the physical reasons underlying the obtained outcomes in terms of c_P , a
466 detailed analysis of the torque coefficient as a function of the azimuthal position of the blade was
467 carried out for each of the investigated TSR regimes. Provided that the torque coefficient trend
468 corresponding to TSR=3.3 has already been discussed in Section 3.3, it was thereby omitted from the
469 comments below.

470 Figure 10 reports the torque profiles corresponding to TSR=2.4. As one can readily notice, a large
471 unsteadiness characterizes the whole torque extraction, which is a typical issue for functioning
472 regimes corresponding to very low TSRs: broad fluctuations are indeed visible within the c_T profiles,
473 regardless of the GF configuration, as a result of the large AoA variations. By a closer examination,
474 it is possible to observe that in the first 90°-100° of the revolution, the baseline and GF_{in} curves
475 basically overlap each other, and the same thing occurs between the GF_{out} and GF_{both} trends. From
476 that point on, the profiles begin diverging one from another, consistently with the fact that the airfoil
477 starts to experience deep stall conditions: the produced torque drops to negative values, and its trend
478 depicts a number of pretty much pronounced and staggered bumps, depending on which airfoil
479 configuration is considered, as far as the azimuthal position of $\vartheta = 180^\circ$ is reached, with a null torque
480 extraction for all the four cases. The first part of the downwind profile, as long as the position of
481 240°-250°, is characterized by a moderate positive torque production, since the upwind extraction has
482 lowered the energy content of the incoming flow. Subsequently, a second conspicuous drop of c_T
483 occurs, which is nothing but a consequence of the vortex structures which have previously detached
484 from the stalled airfoil within the 100°-180° range and have been conveyed downstream, eventually
485 intercepting the blade itself.

486 Moving forward to the higher simulated TSRs, Figure 11 reports the torque profiles corresponding
487 to the TSRs of 3.9, 4.5 and 6.0. As discussed, these functioning conditions are expected to be
488 characterized by progressively narrower AoA ranges, thus the impact of GFs was attended to be
489 progressively reduced, or even detrimental in some cases due to the additional drag. Concerning the
490 TSR=3.9, and referring to what has previously been commented about the c_P values reported in Figure
491 9, the fact that the GF_{both} and GF_{out} configurations give rise to the same c_P is easily understandable
492 from Figure 11: in fact, whilst the former provides a slightly poorer performance between 0° and
493 120°, so does the latter from 210° to 360°, resulting exactly in the same mean c_P . However, a little c_T
494 oscillation is actually observable within the first 45° of the upwind region, for the GF_{both}
495 configuration. This is a signal that vortex shedding, even if at a mild intensity, is beginning to develop
496 within the wake of that airfoil. Furthermore, the higher c_T achieved in the downwind region by the
497 GF_{in} arrangement is due to the favourable matching between the GF position and the angles of
498 incidence experienced by the airfoil, as already explained in Section 3.3 for the case of TSR=3.3.

499 Focusing now on $TSR=4.5$, one can firstly appreciate that its corresponding torque profiles are by
500 far similar to the previous TSR , especially within the upwind part of the revolution. An equalization
501 between the GF_{both} and the baseline smooth configurations occurs this time, in every way similar to
502 what previously occurred for the GF_{both} and GF_{out} cases. The same occurrence happens for the
503 GF_{in} and GF_{out} arrangements, too. What matters more at this TSR , however, is that the onset of
504 vortex shedding is clearly visible this time over the final portion of the downwind half and the
505 beginning of the upwind one for the torque profile corresponding to the GF_{both} configuration.

506 Finally, the reason why the GF_{both} configuration involves such a poor power extraction at
507 $TSR=6.0$ (i.e. the one with the narrowest AoA range) is readily understandable from Figure 11. A
508 massive presence of vortex shedding is indeed clearly visible over most of the downwind half and the
509 beginning of the upwind one for the torque profile corresponding to this configuration. As one can
510 conclude from the discussion provided in Section 3.4 for the 4% flap, this is indeed the worst
511 situation in terms of shedding promotion: in fact, despite the smaller GF, the TSR is now increased,
512 hence the angle of attack over the airfoil is averagely decreased and eventually the 2% flap becomes
513 big enough to make shedding vortices arise. By the way, looking closely to the last 70 degrees of the
514 downwind torque profile of the GF_{out} configuration, it is possible to identify a barely outlined
515 oscillation of the c_T : this means that not even this GF arrangement is able to totally prevent the onset
516 of vortex shedding, because of the excessive energy extraction within the upwind region of the
517 revolution.

518 These observations are confirmed by Figure 12, where the contours of the dimensionless vorticity
519 are reported for the four analyzed airfoil configurations at the azimuthal position of 312 deg. As a
520 further evidence, Figure 13 provides the pressure coefficient distribution on the airfoil, for the same
521 azimuthal position. As apparent, the GF_{in} configuration turns out to be the only one that allows a
522 torque enhancement without involving the onset of the aforementioned shedding instabilities.

523 3.6 GF effects on the full three-blade case-study Darrieus turbine

524 Once the prospects of GFs for power enhancement of blades in cycloidal motion were assessed
525 on the single-blade study cases, their effect on a real 3-blade turbine was evaluated. In this case, the
526 mutual interaction of the blades and their wakes was indeed accounted for.

527 Before going into the discussion reported below, it is worth explaining why the 3% flap size was
528 considered the most reasonable choice for the simulations in case of the full 3-blade rotor. This value
529 was indeed thought to represent a good compromise between two requirements. On one side, a higher
530 flap might have been excessive, probably inducing vortex shedding within the wake of the airfoil and
531 worsening the performance of the turbine. On the other, the 2% flap would have brought no
532 appreciable effects: in fact, the interference effect of the upwind region of the revolution on the
533 downwind one is significantly magnified for the full three-blade rotor, in comparison with the single
534 rotating airfoil of the previous Sections. Consequently, the boosting effect of the GF could not have
535 been detected.

536 Figure 14 provides the power coefficient trends corresponding to the four compared
537 configurations. Please note that the curve of the baseline smooth configuration was reproduced from
538 [30], where the same case-study rotor was studied. Provided that the peak value of the power
539 coefficient therein occurred for $TSR=2.64$, this was the first investigated functioning regime.

540 From a perusal of Figure 14, it is first apparent that the GF_{both} arrangement gives rise to a
541 dramatic worsening of the performance at $TSR=2.64$, with a drop of -27.2% in comparison with the
542 baseline smooth configuration. On the other side, the GF_{in} solution results in a 3.7% enhancement
543 of the power coefficient, while the GF_{out} arrangement produces only a very mild decrease of it
544 (-1.5%).

545 The second set of simulations was run at $TSR=2.4$. The outcomes revealed that both the GF_{in} and
546 GF_{both} configurations led to a significant power extraction improvement, which was of 21.3% and
547 17.4%, respectively. Again, the GF_{out} solution resulted instead in basically no appreciable variation
548 in comparison with the baseline smooth case.

549 As regards the TSR of 2.1, it's interesting to note the 52.6% power increase brought by the *GFboth*
550 configuration, as this could be beneficial for the start-up of the turbine (even if this advantage would
551 be nullified by the subsequent performance drop after $TSR=2.4$).

552 Moving rightwards to the stable half of the curve, it's apparent that the addition of the GF brings
553 now a decline of the performance, both in the *GFin* and in the *GFout* case. In particular, at the highest
554 simulated TSR (namely, $TSR=4.04$), a -81% variation is involved by the *GFin* solution, in
555 comparison with the baseline arrangement. It's interesting to highlight that this trend is now reversed
556 in comparison with the single rotating airfoil featuring the *GFin* or *GFout* configurations, which
557 instead provided a better performance at high TSRs in comparison with the baseline smooth
558 configuration (see Figure 9). Furthermore, whereas in that case (single airfoil) the *GFin* and *GFout*
559 solutions gave almost the same results for all the TSRs, here the *GFout* configuration constantly
560 generates lower power coefficients in comparison with the *GFin* solution.

561 To better understand the physical reasons which had led to these results, a detailed analysis of the
562 torque profiles corresponding to each TSR was carried out. Please note that the discussion reported
563 below refers to the torque extraction of a single blade among the three belonging to the full rotor: the
564 complete profile may be derived simply summing the contributions of the three blades, bearing in
565 mind that they are shifted by 120° from each other.

566 Figure 15 reports the torque profiles over the complete revolution at $TSR=2.4$ and $TSR=2.64$. It's
567 therein clarified why the *GFin* and *GFboth* configurations lead to a power production augmentation
568 in comparison with the baseline smooth case. This is particularly apparent at $TSR=2.4$, where the
569 power extraction provided by the unmodified rotor is quite poor. The torque profile corresponding to
570 the baseline case is indeed characterized by an unstable trend, with a negative torque coefficient
571 between 350° and 30° , as well as between 125° and 180° . The boosting effect of the *GFin*
572 arrangement is instead evident: despite a mildly poorer performance between 15° and 95° , it provides
573 a higher efficiency for the remaining portion of the upwind half, and, more importantly, it ensures an
574 excellent behaviour through the whole downwind region, with a nearly flat trend between 210° and
575 340° . The *GFboth* configuration also provides a good performance, even if this is due different
576 reasons. In fact, the torque remains negative until the position $\vartheta = 40^\circ$, afterward it turns positive and
577 increases steeply to reach a very high peak, corresponding to $\vartheta = 90^\circ$. The remaining part of the
578 upwind zone is then characterized by a constantly higher torque extraction in comparison with the
579 other two configurations, at least until $\vartheta = 170^\circ$. Subsequently, the downwind half looks to provide a
580 power production which is slightly lower than the one of the baseline configuration: this is likely due
581 both to the large energy amount which has already been extracted upwind, and also to the outer
582 portion of the GF, which matches improperly with the relative speed direction and nullifies the
583 benefits of the inner portion. The latter issue even more applies to the *GFout* case, whose downwind
584 performance is always the worst among the other configurations, both at $TSR=2.4$ and $TSR=2.64$. In
585 particular, when this solution is compared to the baseline smooth case, it shows a significantly higher
586 efficiency within the upwind half, though this is then entirely outweighed by the lower downwind
587 power extraction, resulting in no net advantage. It's also interesting to compare the performance of
588 the *GFout* configuration with the one provided by the *GFin* solution. In fact, the situation is reversed
589 for the latter, as its upwind power production is lower than the baseline rotor, whereas the GF boosts
590 it downwind. When the hypothetical one-blade rotor was tested, this resulted in an equivalent average
591 performance in comparison with the *GFout* case (see Section 3.5), but the same thing doesn't happen
592 now. This can be justified by the stronger interference effect produced by the three-bladed rotor in
593 comparison with the single rotating airfoil: this issue is even more magnified by the *GFout*
594 configuration, which involves practically no flow incidence on the airfoils in the downwind portion.
595 Apparently, this fact penalises the overall performance more than the *GFin* does within the upwind
596 half of the revolution.

597 Moving forward to $TSR=2.64$, a more stable behaviour is apparent there for the baseline smooth
598 configuration, with a conspicuous reduction of the negative torque region which occurred at $TSR=2.4$
599 between 125° and 180° . Furthermore, a higher performance is apparent through the entire second half

600 of the upwind zone, resulting in an average larger power extraction over the whole revolution. Similar
601 considerations apply also to the *GF_{in}* configuration, even if the torque profile corresponding to it
602 turns out to be not so modified in comparison to the one of TSR=2.4. A substantial change occurs
603 instead for the torque profile involved by the *GF_{both}* configuration, which explains the abrupt drop
604 of the power coefficient reported in Figure 14. Despite this arrangement still provides the highest
605 peak torque in the upwind region, a very poor performance characterizes the whole downwind half:
606 but, more importantly, evident fluctuations appear within the torque profile, starting from $\vartheta = 230^\circ$
607 and continuing until the position $\vartheta = 45^\circ$. By the way, the onset of these instabilities could be
608 expected, since they had already arisen in the first 40° of the upwind half of the same torque profile,
609 at TSR=2.4. These oscillations, which are due to the presence of strong vortices shedding from the
610 rotating airfoil, are detrimental for the torque extraction, whose curve is heavily shifted downwards.

611 Figure 16 reports a comparison between the torque profiles produced by the different tested airfoil
612 configurations at TSR=2.1, 3.3 and 4.04. As expected, because of the high irregularity which affects
613 the flow field at low TSRs, the torque profile corresponding to TSR=2.1 is characterized by
614 continuous oscillations between positive and negative values. As discussed in previous studies (e.g.
615 [59]), this is due to the fact that, at low TSRs, the AoA variation is so large to let the airfoil
616 experiencing deep stall, with massive drop of performance and the detachment of macro-vortices that
617 are detached from the blades and then convected downwind by the flow. The interaction of these
618 vortices with the downwind blades contributes to the high variability of the torque profile: for this
619 reason, the effect of the GF doesn't stand out clearly at this rotating regime, and it did not make sense
620 to carry out a specific discussion about that.

621 Conversely, the higher TSRs involve a much more regular curve, with a positive upwind peak
622 followed by a downwind flat trend. Accordingly, the GF effect is much better outlined at these
623 functioning regimes. Consistently with the poorer performance depicted in Figure 16, the
624 modification induced by the GF at TSR=3.3 is slightly disadvantageous as a whole, both in the *GF_{in}*
625 and the *GF_{out}* case. In fact, despite the former ensures a mildly better performance within the entire
626 downwind zone, not the same occurrence is visible in the upwind half: after just 20° , the torque profile
627 of the *GF_{in}* configuration drops under the one of the baseline smooth case, staying below it for the
628 whole upwind portion of the revolution. On the other hand, as usual, the *GF_{out}* arrangement overly
629 boosts the upwind extraction, which is then paid with a resistant torque all along the downwind half.
630 Furthermore, the latter is also characterized by fluctuations due to the onset of vortex shedding.

631 Moving forward to TSR=4.04, the reason underlying the bad performance emerging from Figure
632 16 is readily apparent. The torque profile is indeed greatly shifted downwards, ensuring positive
633 torques only between 60° and 145° . But, what matters more, noticeable oscillations affect the entire
634 torque extraction, revealing that intense shedding vortices are constantly detaching from the blades
635 during their revolution.

636 4. Conclusions

637 The possible benefits deriving from the application of Gurney Flaps on the blades of a Darrieus
638 VAWT were investigated within the present work. These devices were in fact thought to represent a
639 simple and effective way to enhance the power extraction capability of those machines (even in a
640 retrofitting strategy), which are experiencing a renewed interest within the wind energy market and
641 research.

642 To properly capture the unsteady aerodynamics, unsteady CFD simulations were needed. Based
643 on previous experience, 2D simulations were thought to represent the best compromise between
644 accuracy and computational cost. Notwithstanding this, the overall computational burden turned out
645 anyway to be significantly high, since a full-unsteady approach, with heavy spatial and temporal
646 refinement levels, was needed to ensure reliable results.

647 The numerical setup used for the analyses was first validated with experimental data, in order to
648 verify that it was able to guarantee an accurate description of the effects of GFs on the aerodynamic
649 behavior of the airfoils. Accordingly, a literature case study was selected, concerning the comparison
650 between the static polars of a NACA0011 airfoil with and without GFs. The airfoil polars were
651 reproduced by means of CFD calculations, and the results showed satisfactory agreement with the
652 reference trends, although some discrepancies were found on the static stall angle predicted by CFD.

653 Subsequently, the effects of mounting GFs on a Darrieus turbine were evaluated. The
654 experimental case study, which was selected for the analyses, featured a three-blade H-Darrieus
655 equipped with a NACA0021 airfoil. A preliminary assessment of the effect of 2% GF on the static
656 polars of this airfoil was carried out, reproducing the same chord Reynolds number experienced by
657 the airfoil during the rotation. The results showed a notable enhancement of the aerodynamic
658 performance of the airfoil, whose peak lift coefficient was increased by 58% in comparison with its
659 baseline configuration. Furthermore, the whole lift curve was strongly shifted upwards, whereas the
660 drag coefficient turned out to be not significantly modified. The static stall angle looked to be only
661 mildly affected by the application of the GF, remaining around 12°.

662 Moving forward from these encouraging results, the effects of the GF were first simulated
663 considering a hypothetical one-blade Darrieus having the exact features of the case study rotor: this
664 allowed to focus on the aerodynamic modifications induced by the GF, without any spurious effect
665 deriving from the multiple blade/wake interactions occurring in a real rotor. Furthermore, thanks to
666 the lighter computational burden, several sensitivity analyses were carried out. First, the functioning
667 regime corresponding to TSR=3.3 was analyzed, and three different mounting configurations were
668 compared, featuring a 2% GF on the inner, on the outer and on both of the sides of the rotating
669 airfoil. Furthermore, the effect of different sizes of the GF on the power extraction capability of the
670 blade was investigated, focusing the analysis only on the latter of the previous three GF configurations
671 and varying its height among 2%, 3% and 4%. Finally, the research was extended to other
672 functioning regimes of the turbine: for each of them, a 2% GF was tested within the configurations
673 reported above, with the aim of predicting the trend of the power curves. For each of the study cases,
674 the performance of the airfoil was compared with its baseline smooth configuration, paying particular
675 attention to the different torque profiles over the complete revolution.

676 The results showed that, if the proper GF configuration is selected, it can provide a notable
677 increase of the aerodynamic performance especially at medium-low TSRs. More in detail, when the
678 2% GF was applied on the inner side of the airfoil, it was proven to guarantee a 23.1% and 14.6%
679 increase of the power coefficient at TSR=3.3 and TSR=3.9, respectively. Moreover, this GF
680 arrangement avoided the onset of vortex shedding at high-TSR rotating regimes, which instead was
681 promoted when the flap was mounted on the outer or on both sides of the airfoils. Besides, when the
682 GF was mounted on the inner of the blade, it provided also a flatter power curve trend with a lower
683 peak TSR in comparison with the baseline configuration, involving interesting implications for the
684 turbine control.

685 As a conclusion of the study, the GF effects were evaluated on the real three-blade case study
686 rotor, in order to achieve some preliminary results for further research. A 3% GF was applied on the
687 airfoils and the same previous GF configurations were compared. Very promising results were found:
688 the power coefficient was increased by 21.3% at TSR=2.4, when the GF was applied on the inner
689 side of the airfoils.

690 The results actually showed that GFs entail the potential of ensuring significant improvements for
691 the energy yield capability of VAWTs. Although these results can be considered pretty innovative,
692 further research is surely needed in order to better assess the benefits of GFs for Darrieus turbines.
693 For example, the implementation of these flaps implies additional material needed for the
694 construction of the machine, with an increase in the drag force experienced by the blades: this
695 unavoidably has an impact on the structural stresses the struts have to bear.

696 Future analyses will investigate different rotor geometries, airfoils and turbine dimensions.
697 Moreover, many other configurations of the GF could be considered and compared: among them,

698 flaps with a tilt angle with respect to the chord of the airfoil, as well as pivoting GFs (which could
 699 switch their position when the blade moves from the upwind to the downwind region), represent only
 700 a few examples of the numerous studies that could be performed in the future.

701 5. Nomenclature

702

703 Acronyms

704	AoA	Angle of Attack	
705	BEM	Blade Element Momentum	
706	CFD	Computational Fluid Dynamics	
707	SST	Shear Stress Transport	
708	TSR	Tip-Speed Ratio	
709	U-RANS	Unsteady Reynolds-Averaged Navier-Stokes	
710	VAWTs	Vertical Axis Wind Turbines	

711

712 Greek symbols

713	α	Angle of Attack (symbol)	[deg]
714	ϑ	Azimuthal Angle	[deg]
715	π	Dimensionless Pressure Coefficient	[-]
716	ω	Specific Turbulence Dissipation Rate	[1/s]
717	Ω	Turbine Revolution Speed	[rad/s]

718

719 Latin symbols

720	c	Blade Chord	[m]
721	c_D	Drag Coefficient	[-]
722	c_L	Lift Coefficient	[-]
723	c_P	Power Coefficient	[-]
724	c_T	Torque Coefficient	[-]
725	D	Rotor Diameter	[m]
726	F_D	Drag Force	[N]
727	F_L	Lift Force	[N]
728	k	Turbulence Kinetic Energy	[m ² /s ²]
729	R	Rotor Radius	[m]
730	Re	Reynolds Number	[-]
731	Re_θ	Momentum Thickness Reynolds Number	[-]
732	U	Undisturbed Wind Speed	[m/s]
733	w	Relative Speed	[m/s]
734	y^+	Dimensionless Wall Distance	[-]

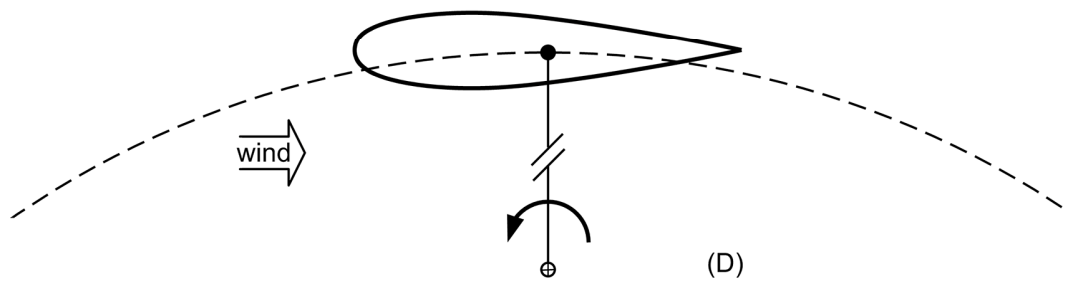
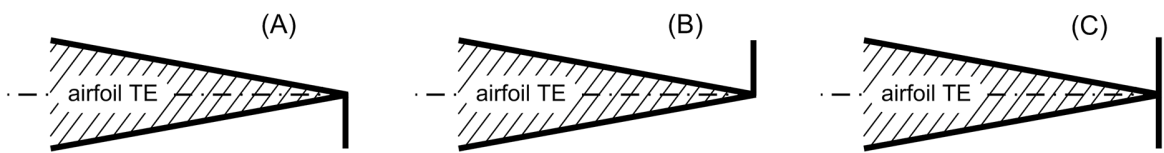
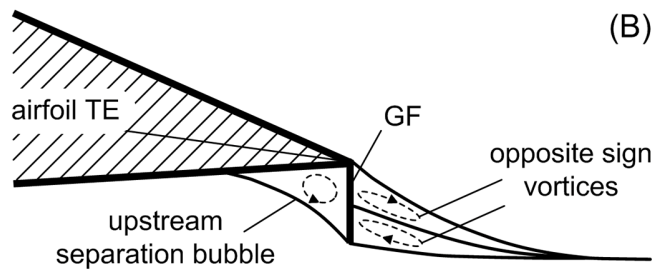
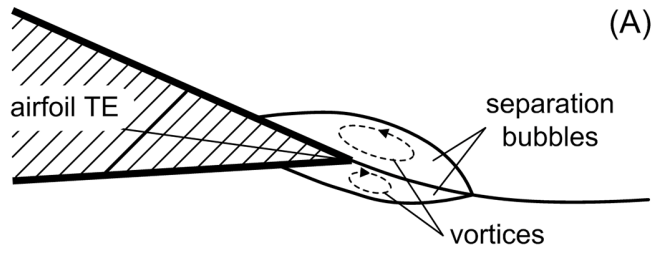
735 6. References

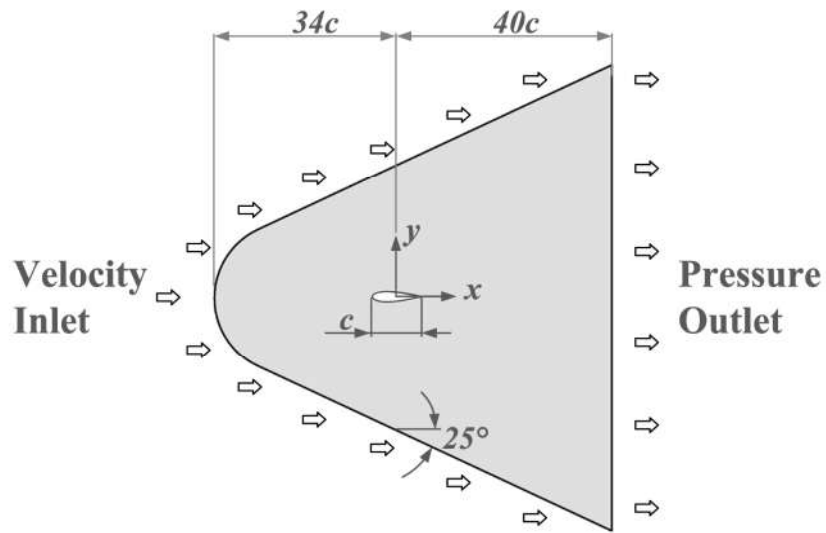
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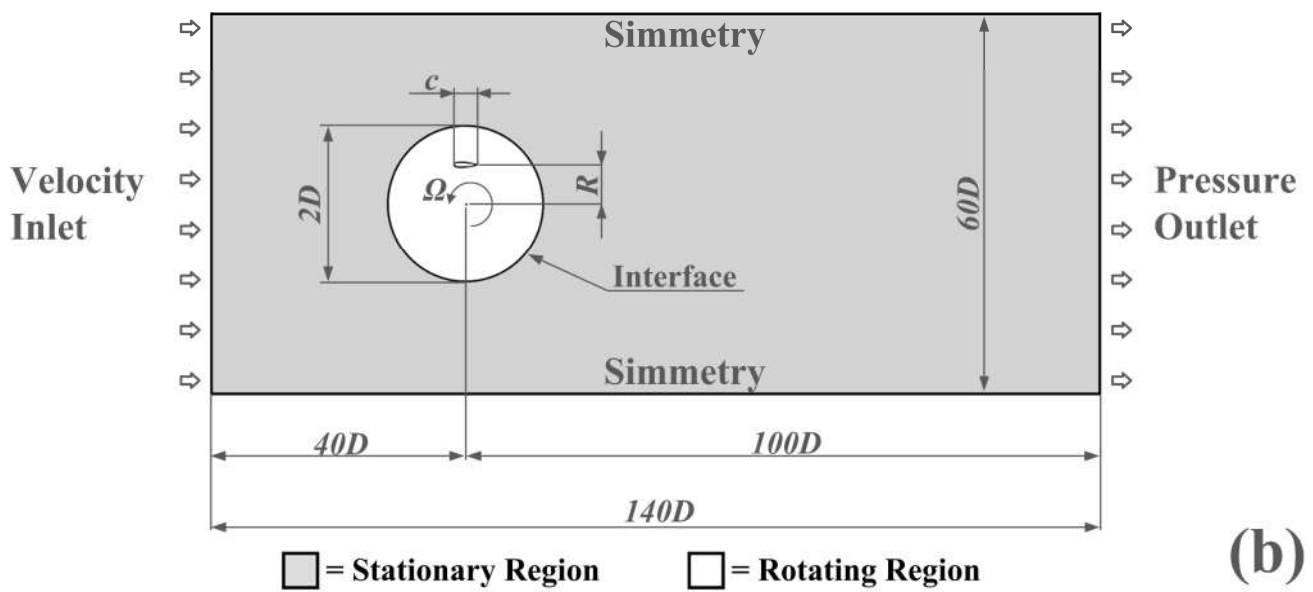
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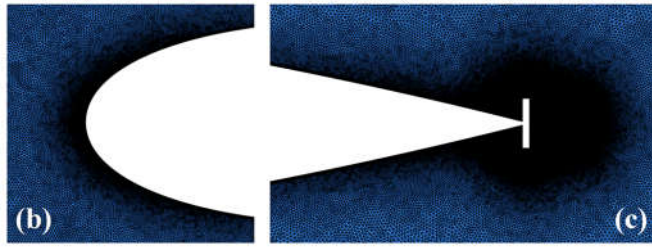
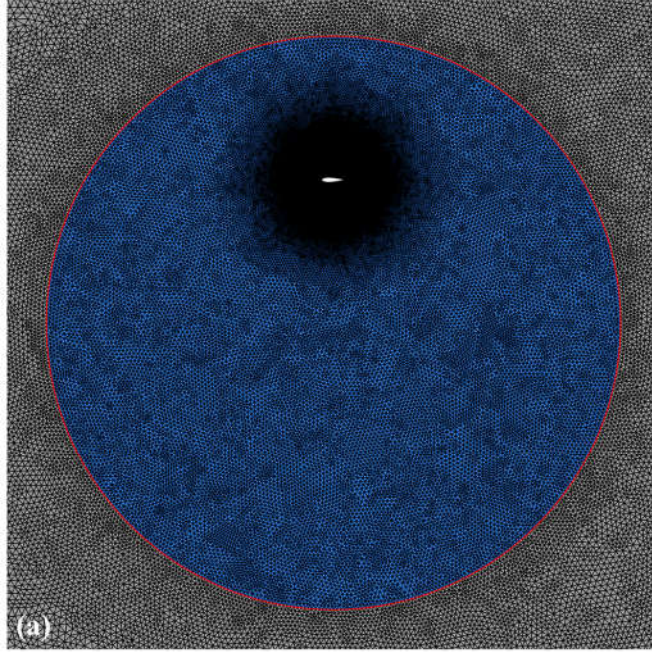


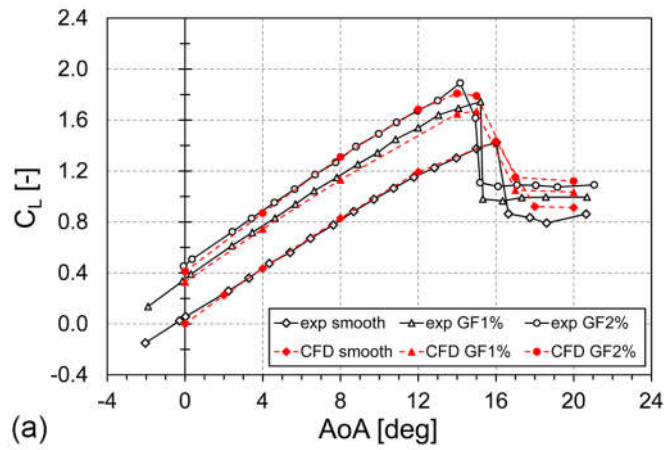


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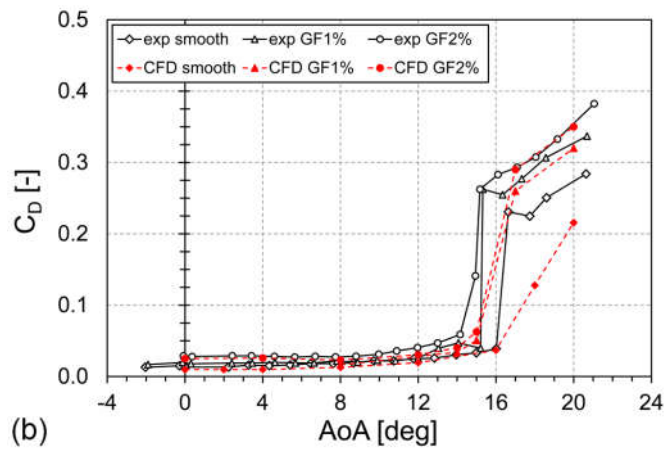


(b)





(a)



(b)

