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CFD three dimensional wake analysis in complex terrain

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Abstract. Even if wind energy technology is nowadays fully developed, the use of wind energy in very complex terrain is still challenging. In particular, it is challenging to characterize the combination effects of wind flow over complex terrain and wake interactions between nearby turbines and this has a practical relevance too, for the perspective of mitigating anomalous vibrations and loads as well improving the farm efficiency. In this work, a very complex terrain site has been analyzed through a Reynolds-averaged CFD (Computational Fluid Dynamics) numerical wind field model; in the simulation the influence of wakes has been included through the Actuator Disk (AD) approach. In particular, the upstream turbine of a cluster of 4 wind turbines having 2.3 MW of rated power is studied. The objective of this study is investigating the full three-dimensional wind field and the impact of three-dimensionality on the evolution of the waked area between nearby turbines. A post-processing method of the output of the CFD simulation is developed and this allows to estimate the wake lateral deviation and the wake width. The reliability of the numerical approach is inspired by and crosschecked through the analysis of the operational SCADA (Supervisory Control and Data Acquisition) data of the cluster of interest.

1. Introduction

The development of onshore wind energy industry [1] has stimulated a certain number of scientific and technological challenges: the comprehension of flow over terrain at the microscale level [2, 3, 4, 5, 6], the assessment of what happens in the downstream area especially when terrain-induced flow acceleration combines with wake interactions [7, 8, 9, 10] between nearby turbines.

Therefore, the scientific literature about wakes in complex terrain [11, 12, 13, 14] has been recently vastly developing. A general boost has been provided by the widespread diffusion of SCADA control systems and by an increasingly open-minded attitude towards the use of data in wind energy industry [15, 16, 17, 18]. An impressive boost, inspiring also the present work, has been provided by the evolution of precision wind measurements techniques, allowing the reconstruction of the full three dimensional wind field. For example, in [13], it is shown, basing on an experimental drone campaign, that in complex terrain the near-wake of a full scale wind turbine extends up to two rotor diameters and is therefore 35% shorter than in flat terrain. In [19], high-frequency time series measurements obtained with remote scanning systems are employed for the analysis of wakes in complex terrain. Similarly to the case of

CFD three dimensional wake analysis in complex terrain

[13], it arises that the waked area is smaller than in complex terrain because wake effects are often overruled by the mixing induced by topology effects.

In [20], the three dimensionality of the waked characteristics of a yawed wind turbine immersed in a turbulent boundary layer is studied: in that work, wind tunnel testing, through high-resolution stereoscopic particle image velocimetry system, is used to measure the three velocity components in the turbine wake under different yaw angles and tip-speed ratios. Some remarkable features of the wakes of yawed turbines, such as the asymmetric distribution of the wake skew angle with respect to the wake center, are highlighted. This is due to the formation of a counter-rotating vortex pair in the wake cross-section as well as the vertical displacement of the wake center.

The test case of this study is the upstream turbine of a cluster of 4 turbines, having 2.3 MW of rated power each, sited in Italy in a very complex terrain. In [21], the cluster is studied through Reynolds-averaged CFD modeling and SCADA data analysis. The objective of this combination of methods is inquiring how much one can understand the three-dimensional wind field through a two-dimensional lens: the wind field at hub height, as predicted by the numerical model and as observed at the nacelle of the wind turbines. The main result of [21] is that observing and interpreting judiciously the wind field at hub height, it is possible to identify the main drivers of the performances of the cluster: most of all, the impressive directional distortion of the wakes induced by the terrain.

These results, as well with those of [20], inspire the idea of improving the comprehension of the three-dimensional nature of wakes in complex terrain through numerical modeling. In this work, a novel post-processing method is developed for elaborating the output of a steady state RANS CFD model. This allows to quantify the lateral deviation and the width of the wake and therefore the impact of three-dimensionality on the evolution of the waked area between nearby turbine.

Summarizing, the structure of the work is as follows: in Section 2, the test case wind farm is described. The methods are described in Section 3. Section 4 is devoted to the collection of the results and, finally, conclusions as well as further directions are drawn in Section 5.

2. The Wind Farm

The cluster of wind turbines is depicted in Figure 1; the black turbine is the upstream one for which the wake development has been simulated. The contour lines allow to appreciate the considerable complexity of the terrain. The inter-turbine distances are indicated in units of rotor diameter. The wind turbines have 2.3 MW of rated power each.

The 270° is a very populated sector of the wind rose for this site. In this regime, turbine T11 is under a full wake from turbine T10 and turbine T12 is under the multiple full wake of turbines T10 and T11. In [22], the distribution of the performances of the cluster when the wind blows from 270° is estimated using SCADA operational data: it arises that, at T12 site, a considerable wake recovery is observed, so that turbine T13 is often the most productive turbine of the cluster. In [21], this picture is interpreted as due to the northward distortion of the wake of T11. This is precisely the effect of the complexity of the terrain. Anyway the cited analysis was performed only observing the 2D wind field distribution at hub height; for a fully three
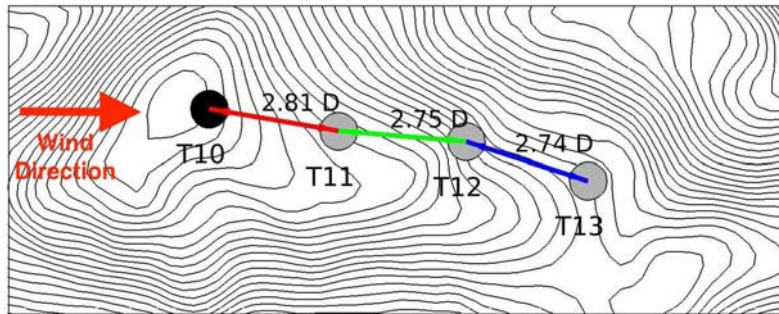
CFD three dimensional wake analysis in complex terrain

Figure 1. The layout of the test case cluster, where D is the rotor diameter.

dimensional insight it is therefore fundamental to explore the behavior of the wake at different heights from ground.

3. The method

The WindSim numerical tool has been employed [2, 5] for the simulations. The inlet boundary is a logarithmic profile blowing from 270°, and the top of the boundary layer is 250 meters. RANS equations are solved through the General Collocated Velocity (GCV) method, for its capability of robust convergence also in very complex terrain. The complexity of the terrain suggests the optimal choice of the turbulence model: RNG k-ϵ is selected, as for example in [23, 24]. The wake interaction was modeled through the Actuator Disk (AD) approach. The used wake model indeed disregards wake rotation and reproduces the speed deficit applying the thrust on the rotor surface: despite its simplicity such a model [25] can be reliable to reproduce the waked flow in the mid to far wake region.

In [21], a method for defining a wake area and a mean wake line was proposed. It is based on the comparison between the simulated free flow wind field and the simulated wind field where the upstream turbine is included and accounted for through the AD model. All the points where, within a certain tolerance, the wind field with the turbine is lower than the free wind field are included in the wake area. The midpoints of each wake section can be computed and they form a wake line. As an example, see Figures 2 and 3.

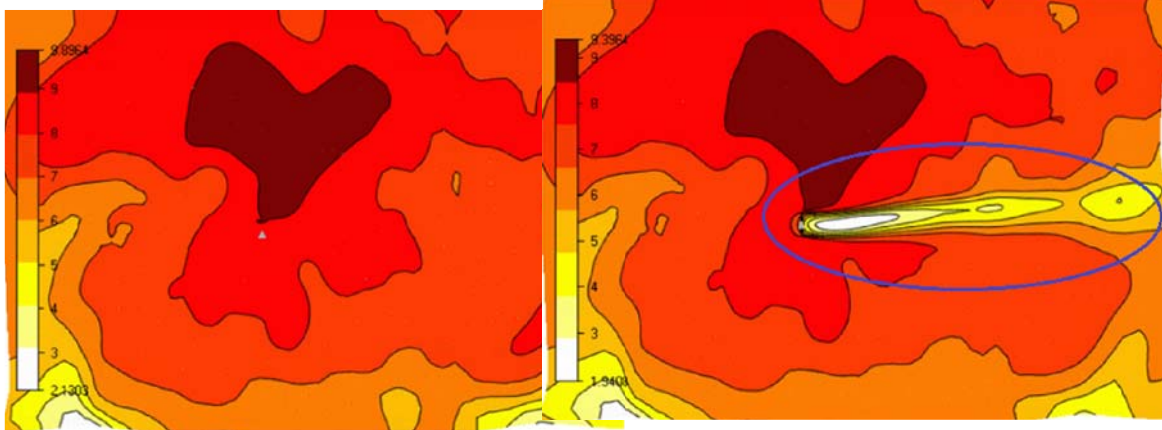*CFD three dimensional wake analysis in complex terrain*

Figure 2. Free flow simulation

Figure 3. Single wake flow simulation: the area of the cluster in circled in blue.

This method is purely geometric, basing on the idea that the wake deficit should be symmetric. In this work, the definition of wake area is improved through the improvement of the post processing acting on the simulated wind field. The center of the wake in the lateral z-direction is defined by looking at the maximum speed deficit for each streamwise x-coordinate and this can be performed at any height from ground y. The comparison between this method and the one from [21] is shown in Figures 4, 5 and 6. In particular, from Figure 6, the role of the terrain in distorting the wake area arises more clearly.
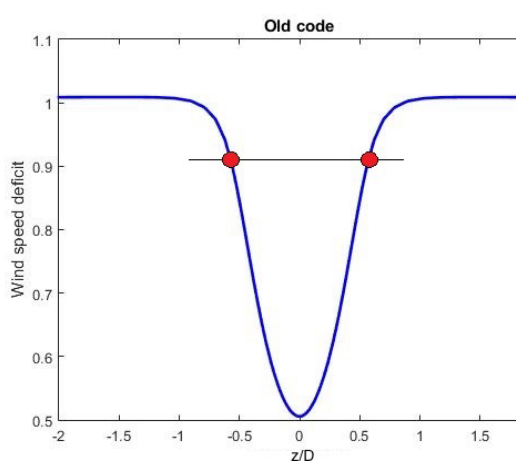

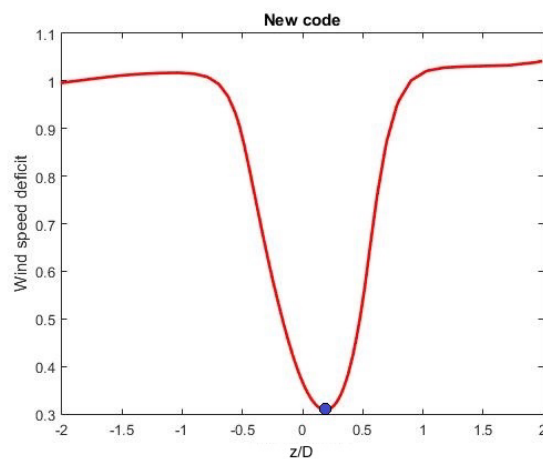
Figure 4. Purely geometrical wake definition

Figure 5. Definition of the wake basing on the speed deficit.
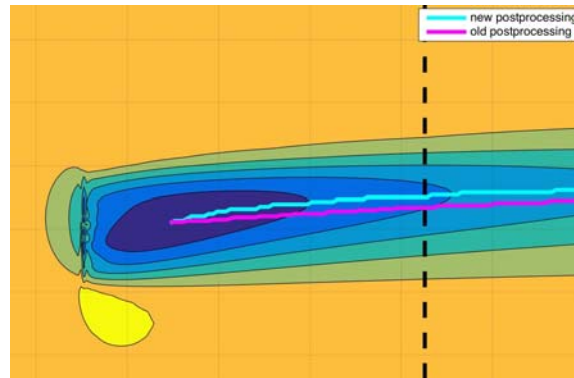
CFD three dimensional wake analysis in complex terrain

Figure 6. The wake line according to geometrical and optimized post-processing, at hub height.

This approach is employed to reconstruct the full three-dimensionality of the wake, by cutting the wind flow, and therefore the wake, in slices: wind intensity planes parallel to the ground at different heights are considered. For each height, the wake section is reconstructed by individuating, as above, the minimum velocity. As a reference for the flow upstream, the distance of two rotor diameters upstream is taken. The renormalization can be relative (referred to the same height), or absolute (referred to the hub height plane). This method provides as output a surface evolving downstream and up and down and this gives insight into the three-dimensional nature of the wake. Further, in this work, the above method is applied in flat terrain and on the real terrain of the wind farm, in order to appreciate the distortion of the wind flow.

4. Results

The results collected here on refer to the three-dimensional evolution of the wake of turbine T10: therefore, the focus is on the single wake case. The results are shown at two distances downstream. These distances have been selected because they have been considered instructive:

- 2.8 rotor diameters downstream, because it is the position (along the streamwise coordinate) of the turbine T11;
- 8.2 rotor diameters downstream, because it is the position (along the streamwise coordinate) of the turbine T13.

In particular, the position of turbine T11 has been selected because how the wake evolves at that position heavily influences (in a far from trivial way [21]) what happens more downstream.

Three heights are reported: hub height and a lower and a upper (symmetrical) height with respect to the hub (at D/3 distance). The upstream and the downstream profiles (normalized, as explained in Section 3, to v_∞ at hub height) are reported as a function of the lateral displacement.

Figures 7 and 8 refer to the flat case and it arises that, as expected, the profiles are symmetric with respect to the z coordinate. The interesting point is that the maximum deficit arises at hub height, with respect to the two other heights, but this

CFD three dimensional wake analysis in complex terrain

effect decreases proceeding downstream and, at 8.2 diameters, the deficit of the lower profile is a bit higher to that of hub height, while the opposite happen for the higher profile.
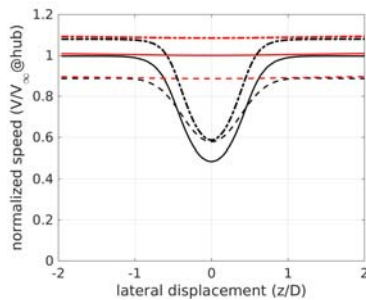

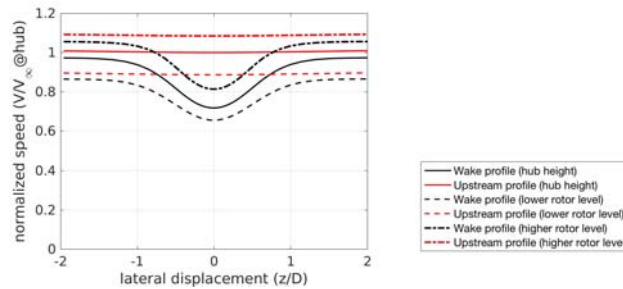**Figure 7.** Wake profile 2.8D downstream (Flat terrain case)

Figure 8. Wake profile 8.2D downstream (Flat terrain case)

In Figures 9 and 10, the results are collected for the simulations on the real terrain. The main feature is that the wake profile isn't symmetric with respect to the lateral displacement and with respect to the height. The former effect is due to the lateral flow distortion, the latter is due to the vertical wind shear. The deformation of the wake becomes more relevant proceeding downstream, and the effect of the topography is so relevant that at T13 site the profile of the wake has a less defined minima (Figure 10). This can be interpreted by looking at the topography of the site (Figure 1): a singularity in the orography occurs, more or less at the streamwise position of turbine T12, and this diffuse the flow horizontally enlarging the width of the wake and deviating its direction. The role of vertical mixing is also important: in the terrain case the width of the wake is higher in all the three investigated levels while in the flat case the width is considerably lower in the upper section of the wake. This picture is confirmed by the final Figures 11 and 12, where the three-dimensional evolution of the wake is represented: the asymmetry of the wake and the role of the terrain and of the wind shear can be fully appreciated.

Another interesting result is that the wake deficit, especially at the beginning of the wake, is stronger for the terrain case; this is also reported in [26] where a similar numerical approach has been used.

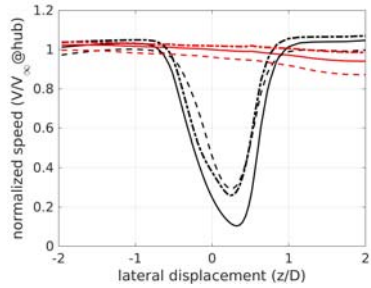*CFD three dimensional wake analysis in complex terrain*

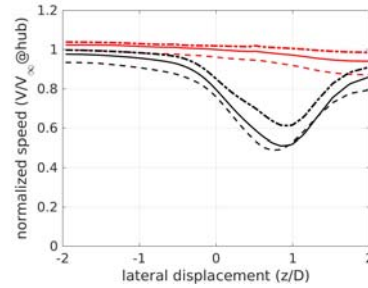**Figure 9.** Wake profile 2.8D downstream (Complex terrain case)

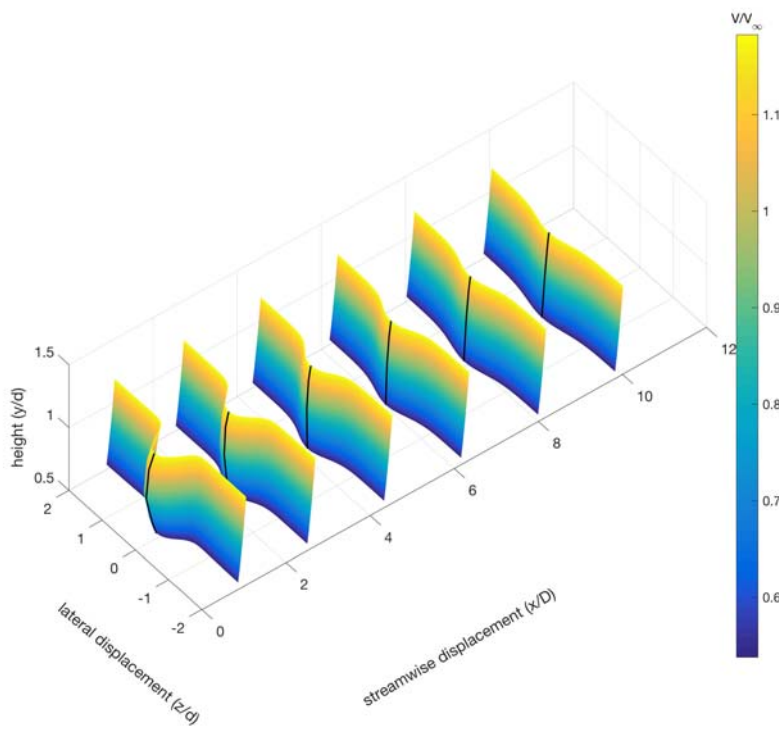**Figure 10.** Wake profile 8.2D downstream (Complex terrain case)

Figure 11. Three dimensional wake analysis with the black line indicating the estimated center (Flat terrain case).

From figure 13 it is also possible to notice how the lateral displacement of the center of the wake has a different behavior according to the height. The lower region, due to the ground influence, tends to be less affected by the general northward deviation induced by the terrain; this also indicate a rotation of the wake volume.
So the general direction of the wake proceeding downstream is defined by the influence of the surface and by the micro-scale inflow defined by the local orography; the effect

CFD three dimensional wake analysis in complex terrain

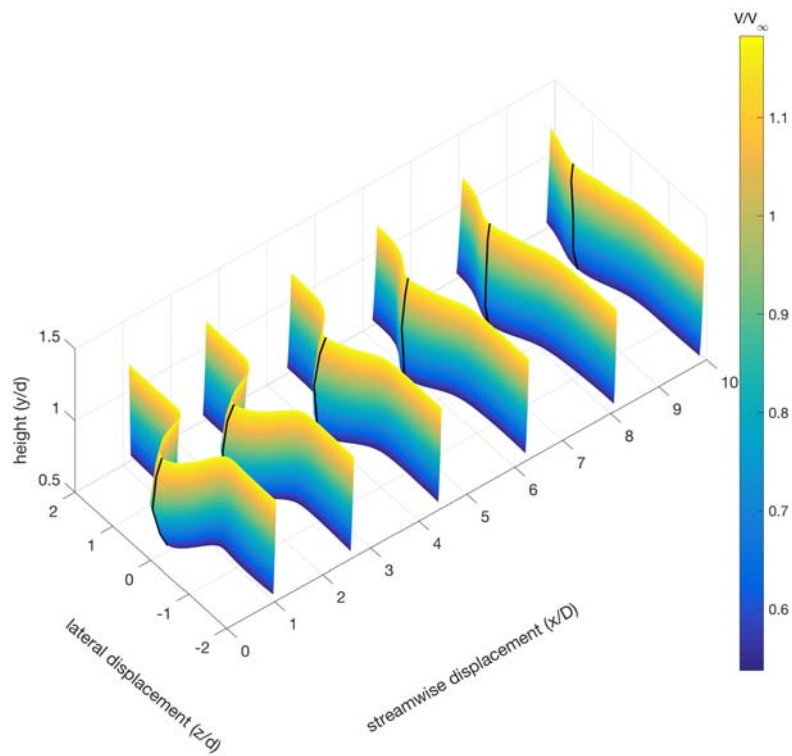of the latter is much more powerful in the upper region of the wake.

Figure 12. Three dimensional wake analysis with the black line indicating the estimated center (Complex terrain case).
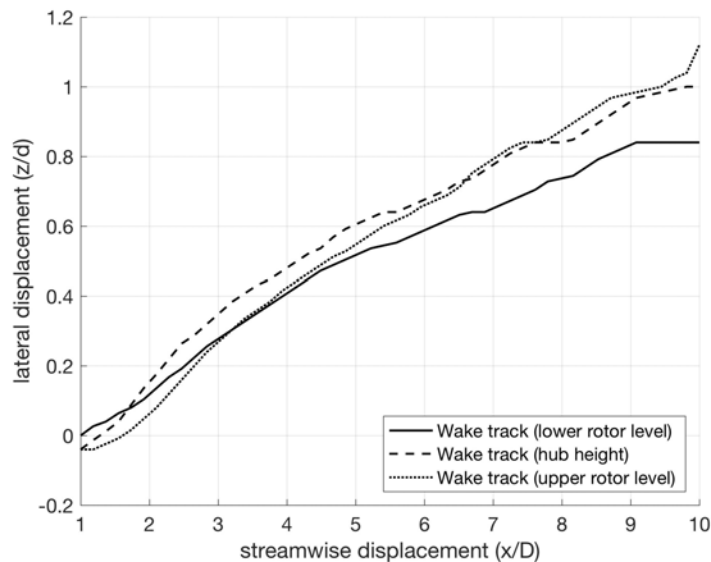
CFD three dimensional wake analysis in complex terrain

Figure 13. Lateral deviation of the wake in the terrain case at different level from ground (lower= hub-D/3 upper=hub+D/3).

5. Discussion and Further Directions

In this work, wind turbine wakes over a very complex terrain have been analyzed. The inspiration to this work comes in general, from the very recent attention on the comprehension of wake recovery in complex terrain [13, 19], and in particular from the study of a cluster of four 2.3 MW wind turbines, sited in southern Italy in a very complex terrain: in [21], the very relevant role of the terrain in distorting the single wake of the upstream wind turbine has been highlighted. Further, in [21], some insights on the evolution of the waked section proceeding downstream have been provided. The straightforward step ahead in the comprehension of this phenomenon is understanding the three-dimensional nature of the wake and its evolution. For these general and particular reasons, the same test case of [21] has been selected and the evolution of the wake of the upstream turbine has been studied when the wind blows from the 270° direction. The main novelty of this work has been the formulation of a new post-processing method of the results from a RANS CFD simulation: by looking at the speed deficit with respect to the v_∞ at hub height, a wake profile can be defined and the main observation is that the terrain distorts the wind flow so that the profile is severely asymmetric with respect to the lateral displacement. This approach has been applied on the wind field at different heights and this allowed to appreciate the effect of the vertical wind shear in the lateral distortion of the wake. In particular, this method has provided further insight into the role of the orography singularities that the wake crosses moving downstream; such terrain details tend to destroy the main structure of the wake and this is a further explanation of the performances of the cluster. Actually, for example in [22] it was noticed that the far downstream T13 wind turbine is the best performing of the cluster when the wind blows from 270°.

CFD three dimensional wake analysis in complex terrain

This work might be fruitful for several further directions: the yawing behavior of the wind turbines, as observed through SCADA data, can in perspective be put in relation with the three-dimensional evolution of the wake. This study also motivates a considerable step forward: the numerical modeling and the experimental study of the mechanical loads and the fatigue behavior of wind turbines undergoing so complex wind flow conditions‡. Further, this framework can be fruitful to interpret experimental data coming from remote scanning systems (as in [19]) spanning three dimensions.

As a future development of the present work also the possible influence of rotation in the evolution of the three dimensional shape of the wake should be investigated; this could be important especially in the near and mid wake region.

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‡ www.softwind.it