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# A new configuration of vertical axis wind turbine: an overview on efficiency and dynamic behaviour

# 垂直轴风力涡轮机的一种新配置：对其效率与动态行为之概览

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**Abstract - Preliminary results obtained for a new configuration "lift based" vertical axis wind turbine is shown. The turbine rotor is a cross flow fan type characterized by a high solidity and having the blades made of high curvature aerodynamic profiles which allow it to start at very low wind speed. A reduced scale model ( Rotor diameter = 250mm, rotor height = 210mm , 24 blades ) has been tested at the Department of Aerospace Engineering of Pisa showing an efficiency of about 18%.**

**During the test, a complete analysis of its aeroelastic response has been carried out using four strain gauges properly placed. Good correlation with FSI and rotor dynamic analyses have been obtained. Furthermore, steady and unsteady CFD simulations have been carried out using Ansys Fluent® Rel.14 and STAR-CCM+® Rel. 6.04 with the Moving Reference Frame and Moving Mesh techniques. CFD analyses confirm the results and give important information about its behaviour and the aerodynamic loads to which it is subjected. Noticeable scale effects have been found numerically, so, the efficiency of a full-scale lift based vertical axis optimized wind turbine is expected to be comparable with lift based horizontal axis wind turbine, i.e. around 30%.**

**A full-scale model of diameter = 1m and height = 1m, not discussed in this work, is currently under construction and will be tested in field to validate the numerical results. An efficiency of about 22% is expected. Since its optimal angular velocity decreases as the scale increases, vibrational phenomena for the full-scale model are supposed to be almost null. Due to its simplicity and its principle of operation, hydrodynamics applications are also quite promising**

**Keywords – Wind energy, Vertical axis wind turbine, VAWT, CFD.**

## I. INTRODUCTION

At the Department of Aerospace Engineering of the University of Pisa a research activity has been carried out concerning the development of a high efficiency vertical axis wind turbine in order to demonstrate the feasibility of a diffuse and competitive (low cost) electrical energy system generation.

Recently new configurations of these machines assume, more and more, the shape of a cross flow fan. These vertical axis wind turbine configurations, studied also by the authors of the present paper, start substantially from an early idea of machine: the *Lafond turbine*, shown in Champly [1], that, from a practical point of view, can be classified as a cross flow fan without the casing.

As it is well known in literature, the efficiency of traditional vertical axis machines are lower than the efficiency of horizontal axis machines. The difference of the turbine studied in this paper consists on the aerodynamic shape of its blades, Fig.1. Promoting several studies (i.e. Di Filippo [2], Russo [3], Atzeni [4] and Bianco [6] ), the authors of the present paper observed that two dimensional CFD analyses, carried out on a Lafond turbine with D = 10m having 24 blades, provided high values of the aerodynamic efficiency of the rotor. Starting from the layout examined by Russo [3], a carbon fiber prototype has been manufactured and tested in the wind tunnel available at the Department of Aerospace Engineering of Pisa (DIA), Fig.2.

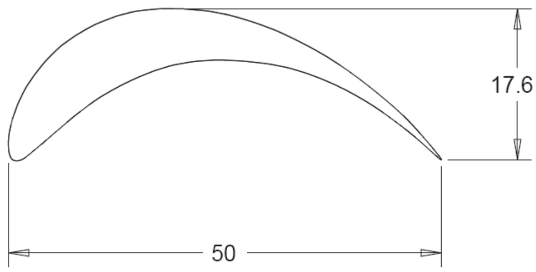


Fig. 1, Blade section. Units: mm. From Russo [3]

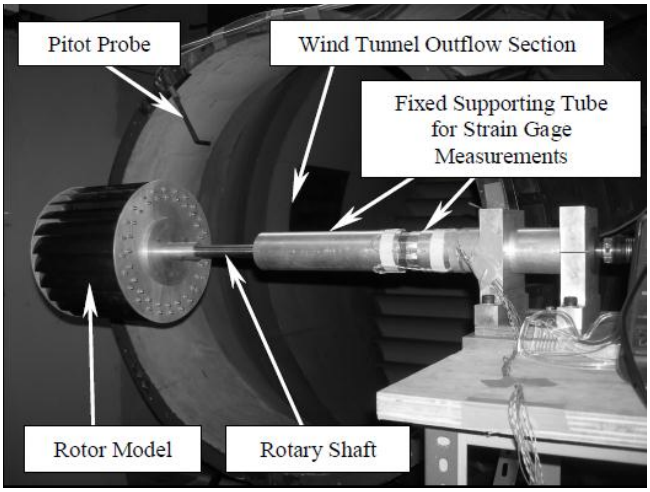


Fig. 2, Sketch of the wind tunnel test arrangement at DIA

Test results have shown that the maximum values of reduced scale rotor efficiency is about 18%, on the other hands, during tests non-negligible vibration effects have been observed.

## II. CFD RESULTS

The ANSYS Fluent® CFD software has been used. The numerical values of torque have been obtained using a first level grid refinement, Fig.5. Numerical results have been obtained using Moving Reference Frame (MRF) technique, applied to a small area surrounding the blades, and K-ε turbulence model in steady state simulations. Results are in good agreement with experimental measurements.

CFD simulation also allowed to visualize flow path lines, shown in Fig. 3, in order to validate the general behaviour of the turbine. As reference has been taken the work from Gabi et al. [8], Fig.4. Nevertheless refining the grid and performing both steady and unsteady analyses applying MRF and Moving Mesh (MM) techniques, higher values of efficiency have been found. From a numerical point of view using a refined is possible to better describe the pressure field on each blade (boundary layer refinement has been also applied ), while from a physical point of view, the vibration effects observed during the tests have, probably, reduced the values of torque measured especially for high values of angular velocity, as shown in Fig.6 for the case at V=15m/s, being

$$\lambda = \frac{\omega R}{V} \tag{1}$$

$$\eta = \frac{Turbine\ power}{Wind\ power} = \frac{\omega\ M_z}{\frac{1}{2}\rho S\ V^3} \tag{2}$$

In any case, the efficiency measured at DIA agrees with some results available in literature concerning small scale rotor models. For example in the work of Colley [7], two dimensional simulations for a rotor with a diameter of 1.4m provide maximum efficiency between 15% and 25%. Have to been taken into account that these results have been obtained using stator-rotor configuration.

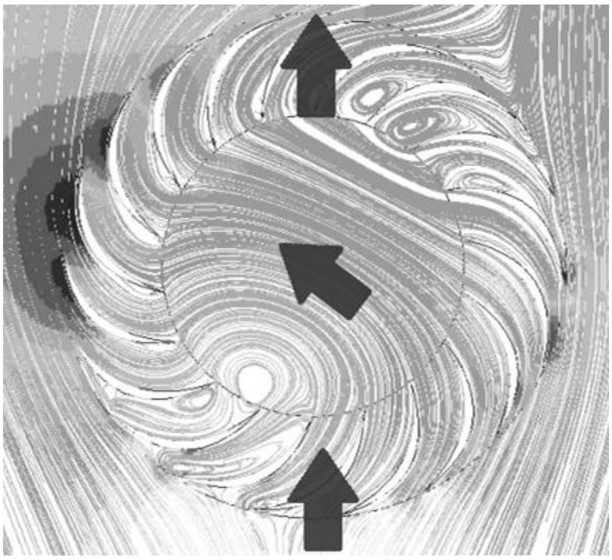

Fig. 3, Path lines - 2D CFD analysis from Russo [3]

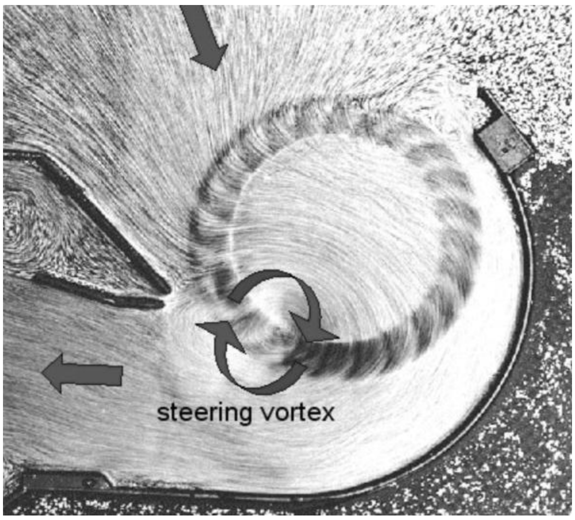


Fig. 4, View of fluid flow for a cross-flow fan in Gabi et al. [8]

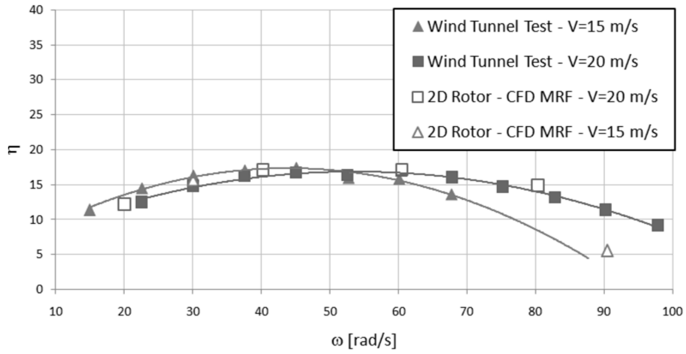


Fig. 5, Measured efficiency vs. 2D CFD MRF steady state analyses.

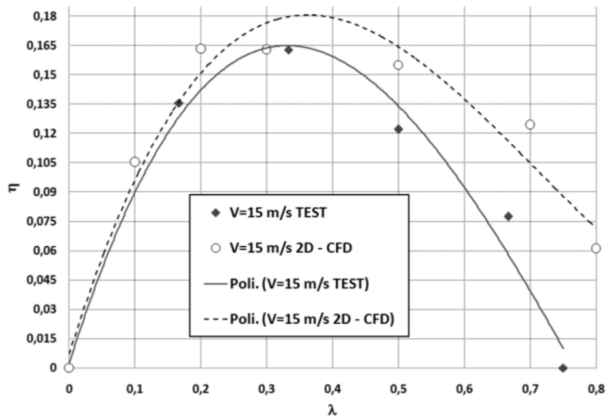


Fig. 6, Efficiency $\eta$ vs. Tip Speed Ratio $\lambda$ – case V = 15 m/s

In order to better understand the physics driving the turbine behaviour, polar plots of the contribute of any single blade have been drawn. In Fig. 7, Fig. 8 and Fig.9 those graph are reported for the case V = 15 m/s, flow coming from 180°. In this way is possible to see which blade is generating torque and which is opposing to the motion. Due to the high solidity coefficient, defined as:

$$\sigma = n\frac{c}{D} \tag{3}$$

These plots also describe the average load on a single blade during a complete rotation. Aerodynamics coefficients for the rotor prototype described above are calculated as:

$$C_{x,y} = \frac{F_{x,y}}{\frac{1}{2}\rho\, S\, V^2} \tag{4}$$

$$C_m = \frac{M_z}{\frac{1}{2}\rho\, S\, V^2 h} \tag{5}$$

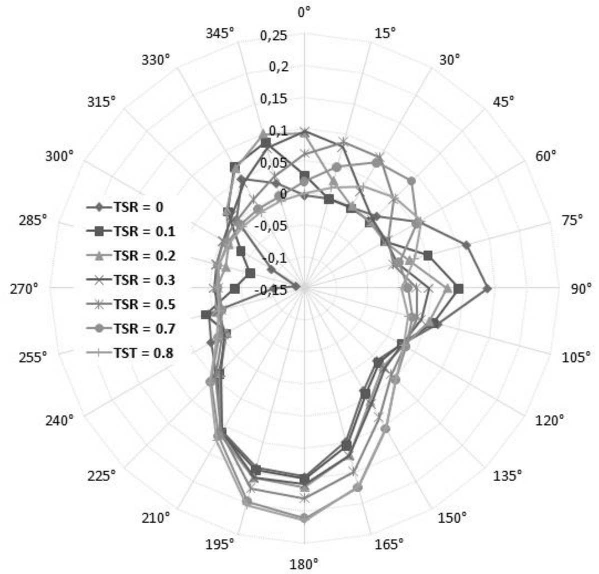


Fig. 7, Cy for the case V = 15 m/s – 2D CFD

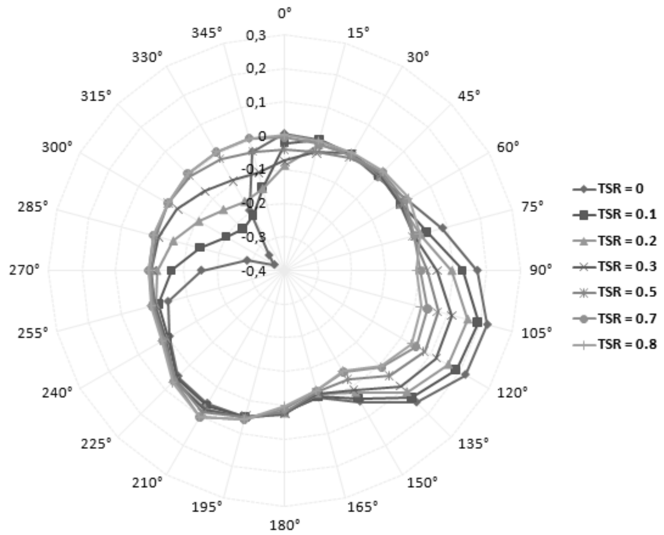


Fig. 8, Cx for the case V = 15 m/s – 2D CFD

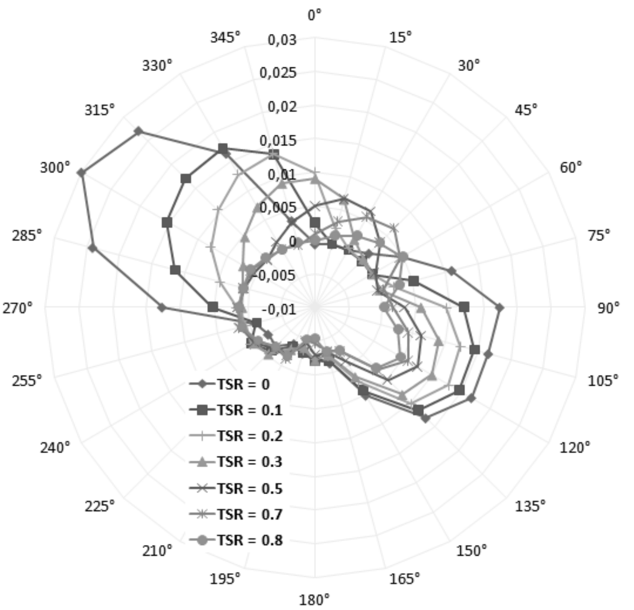


Fig. 9, Cm for the case V = 15 m/s – 2D CFD

The total values of these coefficients is reported for the case V = 15 m/s in Fig. 10. As can be seen the total Cy coefficient, namely the in-line load, tends to approach a constant value as the TSR value increase, while the Cx coefficient, namely the cross-flow load, change direction during the motion. It is important to underline that the Cx value is very low in the range of maximum efficiency.

No information are available at the moment on the value of axial forces and on the torque coefficient with respect to the other axes

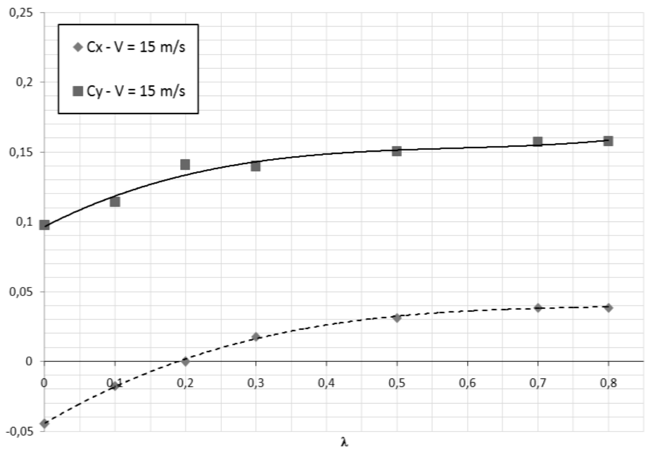


Fig. 10, Load coefficients for the case V = 15 m/s – 2D CFD

## II. VIBRATIONAL ANALYSIS

As has already been mentioned, vibrational phenomena have been observed during the test. Load measurements were taken installing four strain gauges on the fixed support surrounding the rotor shaft, as described in Bianco [6] and Atzeni [5].

Load measurements were affected by inertial forces and, for this reason, no comparison between test and simulation is available. By the way sampling the strain gauges output signal and applying to it an FFT analysis, It has been possible to measure the complete rotor dynamical behaviour of the prototype. Waterfall plot have been drawn as shown in Fig. 11 and Fig.12, respectively the in-line Fy load and the cross-flow Fx load.

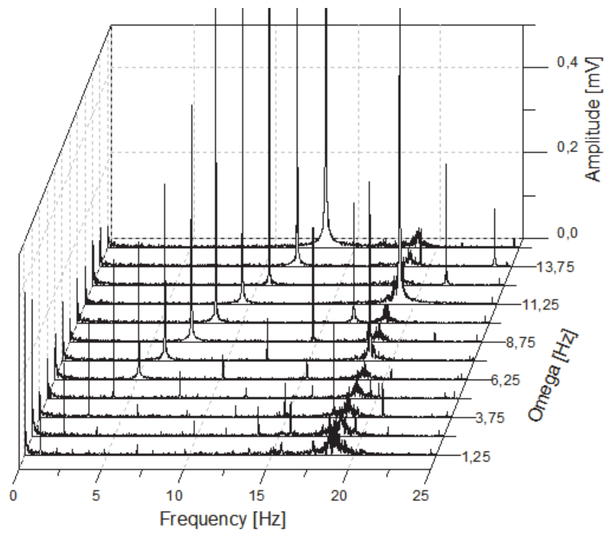


Fig. 11, Fy waterfall plot – Test

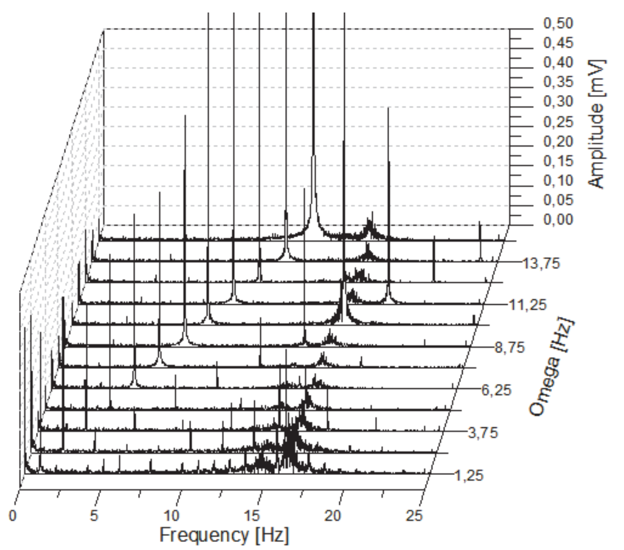


Fig. 12, Fx waterfall plot – Test

According to literature, for example Nelson [9] and Genta [10], combined effects of rotor dynamic natural response mode and first flexional response mode are clearly visible. Response amplitude is amplified in the range of angular velocity between 8 Hz – 15 Hz, namely for TSR between 0.42 – 0.8, exactly in the range of efficiency loss previously shown in Fig.6. Synchronous whirl and second whirl are clearly detectable. The slight difference between first natural mode in Y ( about 18 Hz ) and X ( about 15 Hz) direction is due to a non complete symmetry of the system. Unfortunately no data are available on rotational dynamics since the first torsional mode was much above the sensitivity of the sensors. By the way unsteady two dimensional CFD simulation showed a frequency content in vortex detachment above 200 Hz.

Is important to underline that whirling phenomena are typical, and almost exclusive, of high rotating speed systems . Due to small displacements it is licit to assume that these phenomena do not affect the 2D assumption used in most of the simulations.

In normal case of wind energy harvesting, hence for dimensional scale of about 3m – 10m, maximum rotational speed for TSR = 0.9 would be between 9 rad/s – 2.7 rad/s at V = 15 m/s. In Bianco [6] and Atzeni [5] is shown that efficiency increase with Reynolds number. For this reason a noticeable scale effect is expected, as shown in Fig.13.

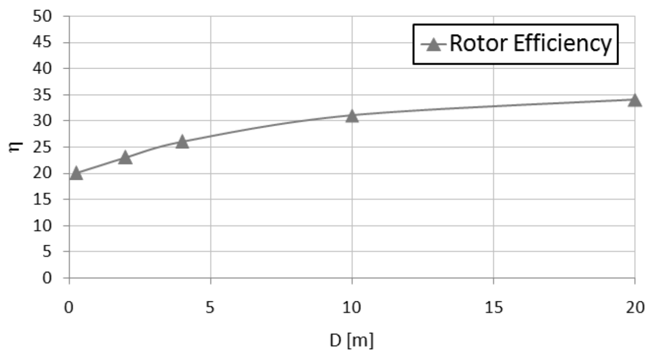


Fig. 13, Efficiency vs rotor scale

## III. CONCLUSIONS

Results from a preliminary campaign tests carried out at the DIA of Pisa on a small scale rotor model have been shown. At the same time a campaign of two dimensional numerical analyses has been executed to estimate the behaviour of the rotor model both in small scale and real scale dimensions. Even if the experimental tests have been affected by unwanted vibration phenomena numerical and experimental results are in a good agreement.

The comparison has been carried out using the Fluent® code (Moving Reference Frame method of analysis applied only to the grid around the blades) with a first level refinement grid. The maximum value of the estimated efficiency is equal to 18%. Refining the mesh It has been possible to detect real behaviour in absence of vibrational phenomena. Dynamic behaviour of the rotor have been also studied in order to validate initial assumption. By the means of CFD simulation a noticeable scale effect has been described. Currently a bigger prototype of 1m of diameter is under development. Because of its simplicity this turbine is also suitable for marine applications.

## NOMENCLATURE

| | |
|---|---|
| $\lambda$ | Tip Speed Ratio (TSR) |
| $\omega$ | Rotational velocity |
| $R$ | External rotor radius |
| $V$ | Wind speed |
| $\sigma$ | Rotor solidity |
| $n$ | Number of blades |
| $c$ | Chord of blade section |
| $D$ | External rotor diameter |
| $F$ | Aerodynamic load |
| $M$ | Aerodynamic torque |
| $C$ | Aerodynamic coefficient |
| $\rho$ | Air density |
| $S$ | Frontal surface ( $D * h$ ) |
| $h$ | Rotor height |
| $\eta$ | Rotor efficiency |
| MRF | Moving Reference Frame technique |
| MM | Moving Mesh technique |
| DIA | Department of Aerospace Engineering ( Pisa, Italy) |

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