NUMERICAL AND EXPERIMENTAL LOADS ANALYSIS ON A HORIZONTAL-AXIS WIND TURBINE IN YAW

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Abstract

The characterization of wind turbines in yawed conditions is one of the most important topics as regards the latest advances in optimizing power production and mechanical behavior in wind farms. The classical wind turbine control strategy consists in keeping the rotor constantly aligned with wind direction: whereas this approach maximizes the power coefficient of each single turbine, it might not be the best solution when, in a wind farm, upwind turbines generate wakes on downwind ones. Considering this, yawing the rotors gives a steer to wakes, improving the flow on downwind turbines. This new kind of control strategy has been attracting the scientific interest not only by an energetic point of view, but also as regards the mechanical behavior of turbines operating not aligned with wind, in particular for what concerns generation of forces and vibrations. On these grounds, the aim of this paper is to study in deep how a wind turbine works on yawed configurations. In order to do this, wind tunnel tests have been performed with yaw angles that range over from $-45°$ to $45°$ on a 2 m. diameter small scale wind turbine. Experimental measurements of forcespower and tower vibrations are then compared with the results of simulations from two different codes. The first, called BEM, is internally developed following the principles of Blade Element Momentum theory and it is used to estimate forces and torque acting on the rotor. The second implemented model is developed using the FAST (Fatigue, Aerodynamics, Structures and Turbulence) software, developed at the National Renewable Energy Laboratory (NREL). FAST simulations provide in output forces, torque and vibrations of tower and blades. Simulations are set up with similar conditions as the wind tunnel tests, with many yaw angles and steady wind speed. One of the main results of this study is that there is a remarkable agreement between simulations and measurements as regards the estimate of the power coefficient C_P in yawed and non-yawed configurations. In spite of this, thrust coefficient C_T is not faithfully estimated when the yaw angles is vanishing. This matter of fact is then explained by the fact that low-fidelity numerical models are not capable in reproducing reliably the effect of the tower blockage, slowing down the air stream in its proximity. As a consequence, when a blade passes close this area of reduced flow speed, the generation of aerodynamic forces decreases. In yawed configurations, this phenomenon is less relevant because of the increased distance between blades and tower on air flow direction.

1 Introduction

The optimization of power production and mechanical behavior of wind turbine through advanced control strategies [1, 2] has been recently becoming one of the main topics in wind energy research. The blade pitch [3, 4] and the yaw management are two very fertile fields of investigation for the research in wind turbine control optimization [5, 6].

The classical approach to control wind turbines nacelle orientation consists in continuously following the wind direction, in order to maintain the rotor axis constantly parallel to air flow. This method guarantees that the single turbine has always the maximum tip-speed ratio and so the maximum energetic production. In spite of this, in wind farm configurations an aspect that has to be considered is that upstream wind turbines generate wakes affecting the downstream ones and this affects the power production [7] and the mechanical loads [8]. By this point of view, new methods for active wind farm control are oriented: the general idea is that a slight decrease of the power produced by the single upwind turbine can optimize the total production of the entire farm. Haces-Fernandes et al. [9] states that a selective turbine deactivation allows an enhancement on wind

farm production and found that improvement is more prominent as the size of the turbines, and so rotor diameter, increases. Another method is the derating [10], that consists on running some turbines with a non-optimal rotational speed in order to catch less energy from air stream but generating less wake effect on downwind turbines: in this case the increase of energy production can range from 1.86% to 6.24%. A novel approach, instead, called wake steering [11, 12, 13], consists in keeping the upwind turbines not aligned with wind direction with the purpose to deviate the wakes and let the downwind turbines to be invested by an air stream with a more energetic content. For a single wind turbine, the power is related to ϕ, the yaw angle between the wind flow and the rotor, with a cosine cube law [14]: as a consequence, the energy production decreases as the yaw angle increases. To understand the net increase of generated power at wind farm level, Archer et al. [12] found that yawing the first row of a turbine array of 20°, the power of the following rows increases profitably (more than the losses of the first row).
To have a wider outlook on wake steering wind farm control, it is necessary to consider not only the effect on energy production, but also the possible side effects on wind turbine structural integrity. For example, Bakshi [15] estimated the reliability of blades in yawed asset, performing a stress analysis in different yaw configurations.

On these grounds, the present study aims at providing a contribution to the experimental analysis and numerical characterization of horizontal-axis wind turbines in yawed conditions. Wind tunnel measurements on a 2 m. diameter turbine are performed, with yaw angles ranging from 0 to $\pm 45°$: forces generated by the rotor, nacelle accelerations, rotational speed and generator power are monitored. Experimental data are then compared to numerical results of simulations performed with two different algorithms. The first is called BEM and has been internally developed according to Blade Element Momentum theory. This code allows an estimation of forces generated by the rotor. The second code, FAST, is developed by NREL, National Renewable Energy Laboratory, Colorado, and is one of the most used software for aeroelastic wind turbine modeling. In FAST, it is possible to obtain in output information concerning power, forces, moments, torque, accelerations and deformations. This software is frequently used to simulate large size wind turbines: by this point of view, one of the purposes of this study is to investigate the reliability of the FAST environment for small wind turbine simulation too. Actually, the critical point is that small wind turbines are strongly affected by fatigue, as a result of their size and the variability of loads , induced by the unsteady wind conditions (especially in urban environment [16]), and modulated by a very high rotational speed [17]. It is therefore interesting to understand the capability of simplified numerical models in reproducing reliably the dynamical behaviour of this kind of devices, especially in yawed conditions.

This paper is organized in the following sections: Section 2 presents the methods and facilities and a discussion on the equipment used. In section 3 the results are presented and examined. Finally Section 4 is devoted to conclusions and future developments.

2 Experimental Set Up and Numerical Models

In this study, experimental tests in wind tunnel and numerical tools are used to characterize the behaviour of a small wind turbine in yawed configuration.

2.1 Wind Turbine and Wind Tunnel for Experimental Tests

The HAWT prototype selected for this work has these main features:

- 40 kg nacelle mass;
- rotor diameter: 2 meters;
- hub height: 1.2 meters;
- hub radius is 0.13 meters;
- minimum chord of the profile: 5 cm. Maximum: 15 cm;
- angle of attack variable between 1.7° and 32°;

- the prototype is equipped with three polymer reinforced with fiberglass blades;
- fixed pitch angle;
- operative rotational speed between 200 and 700 RPM;
- 3 kW of maximum power;
- electric control based on experimental optimal power curve.

In Fig. 1 the test case wind turbine placed inside the wind tunnel is represented; the configuration in the Figure is at 0° of yaw angle but many tests have been performed with yaw angles of up to ±45°.
The wind tunnel used for this research is located at the Department of Engineering at the University of Perugia, Italy (www.windtunnel.unipg.it). The facility consists on a closed loop, open test chamber wind tunnel with a squared cross section of the ducts of 2.2 m. per side. The recovery section is about 2.7 m. x 2.7 m. A 375 kW electric motor puts in rotation a fan that is able to produce variable wind speed in the test section up to 45 m/s. A peculiar characteristic of this tunnel is the extremely low turbulence of the air flow that can be quantified in 0.4%. The wind speed is measured by a Pitot tube and a cup anemometer placed at the inlet section. In Figure 2 a scheme of the wind tunnel is reported.

Figure 1: The small HAWT in the wind tunnel open test section.

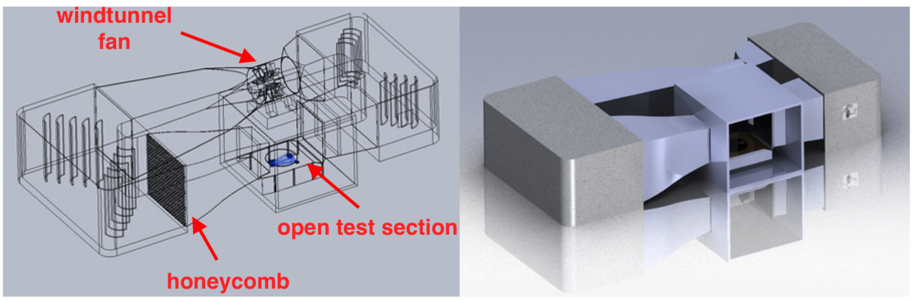

Figure 2: A sketch of the wind tunnel.

As the test section of the wind tunnel is not a free field, it has to be considered a confined environment where the airflow gets modified by the presence of the turbine itself: this phenomenon is called blockage. To consider the blockage, in this discussion wind velocities and thrust or power coefficients will be scaled by a corrective factor, BF (Blockage Factor), estimated following Kinsey and Dumas [18] as in eq.1:

$$BF = \frac{U}{U'}, \tag{1}$$

where U is the free stream wind speed in the wind tunnel with the rotor and U' without the presence of the rotor. Using the blockage factor, it is possible to correct both power and thrust coefficients as expressed by eq.2 and eq. 3:

$$C_P' = C_P \cdot \left(\frac{U}{U'}\right)^3 = C_P \cdot BF^3 \tag{2}$$

$$C_T' = C_T \cdot \left(\frac{U}{U'}\right)^2 = C_T \cdot BF^2, \tag{3}$$

where C_P' and C_T' are the corrected power and thrust coefficient. Previous experimental and numerical studies, in particular Eltayesh et al. [19], have been devoted to the analysis of the blockage factor of the wind tunnel of University of Perugia and the results have been employed for the purpose of this study to correctly estimate the reference free wind speed. According to this, to reliably compare numerical and experimental tests, it should be intended that the C_P and C_T factors obtained from simulations are the corrected ones.
The HAWT has been subjected to steady wind time series having duration of 60 s. During each time series, the yaw angle has a fixed value. The tested yaw angles are:

- 0°;
- ±22.5°
- ±45°.

The selected wind intensity is 10 m/s and some tests have been performed at 8 m/s too.

2.2 The FAST Software

FAST (Fatigue, Aerodynamics, Structures,and Turbulence) is an open-source aeroelastic software developed by NREL (National Renewable Energy Laboratory) and it is used to perform simulations of energetic and mechanical behaviour of horizontal axis wind turbines.
This software offers many alternatives to customize the modeling of turbine components. Electric generator, yaw controller, pitch controller and shaft brake can be modeled in many ways; the most used includes the use of subroutines, look up tables and the interface with external software environments. The number of input files depends on the characteristics of the simulation. In this test the employed input files are:

- Primary: is the main file where simulation parameters can be setted and contains the link to the other files.
- InflowWind: this file describes the wind characteristics. Data about wind speed magnitude,vertical and horizontal components has to be implemented in this file. In addition, it contains the spatial discretization resolution.
- AeroDyn: it includes environment air condition, links to the table of blade airfoils polars, and tower aerodynamic properties.
- ElastoDyn: in this file, the wind turbine mechanical design (pre-cone, tilt angle, masses and inertia) is described. Links to blades and tower shape modes are also included.
- ServoDyn: it manages the behavior of the controllers.Through this file it is possible to implement generator, pitch, yaw and braking models.

Figure 3 is a block chart representing how the files interact during the simulation running.

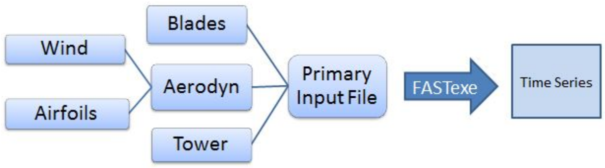

Figure 3: A flowchart of the FAST simulation.

As usual for small wind turbines, the model studied in this paper does not have an active pitch or yaw control, as discussed for example in Scappaticci [20]. To meet market requests and in consideration of the lack of adequate spaces to house actuators, small wind turbines are typically not equipped with advanced control systems. For this reason, in ServoDyn, only the electric generator is modeled. FAST offers many solutions to set up the simulation of generator, in this case, a look up table is considered the best solution. The of external software (like Simulink) is a better choice when PID (Proportional, Integrative, Derivative) controllers have to be implemented, especially for unsteady simulations. In the present paper, instead, simulations are always performed in steady conditions. Neither the default generator model, present in FAST, can be profitably used because it is arranged for large wind turbines. According to this, the choice of look-up table is the most suited among all the possibilities.
Look-up table creates a relationship between the instant rotational speed of the shaft and the resistant torque that has to be applied. Electric generator response is tested experimentally in wind tunnel steady runs with variable wind speed. In this way, once the system reaches the equilibrium, shaft speed and the corresponding torque is collected and than used to create the look up table. It has to be noticed that turbine power controller works according to MPPT (Maximum Power Point Tracking) in order to always find the best performance in terms of power production. FAST allows to impose and keep fixed the the yaw angle in ElastoDyn file. The tested yaw angles are the same as the experimental ones: 0° , ±22.5° and ±45°.

2.3 The BEM Algorithm

The second numerical framework used to estimate mechanical loads on wind turbine is internally developed on the grounds of the BEM (Blade Element Momentum) theory. Many handbooks on wind turbine aerodynamics explain this mathematical approach; in the following, we refer to a summary by Burton[21]. Drag and lift coefficients are defined in eq.4 and eq.5:

$$C_{lift} = 2\frac{L}{\rho A_{ref} U_\infty^2} \tag{4}$$

$$C_{drag} = 2\frac{D}{\rho A_{ref} U_\infty^2}, \tag{5}$$

where L and D are the aerodynamic lift and drag forces; ρ the air density; A_{ref} the area of wind turbine rotor and U_∞ the free stream wind speed. Moreover, labeled as U_d the wind speed at the disk, it is possible to introduce the axial induction factor a', eq.6:

$$a = \frac{U_\infty - U_d}{U_\infty} \tag{6}$$

To keep in account the rotation effect that the disk imparts to the downstream flow, the a' coefficient is introduced, eq.7

$$a' = \frac{1}{2\Omega}\omega, \tag{7}$$

labeled as ω the angular velocity of the wake imparted by the rotor, whose velocity is Ω. Using the a factor, it is possible to rewrite the axial and tangential speeds as eq.:

$$V_x = U_\infty(1-a) \qquad V_y = \Omega R(1+a). \tag{8}$$

After the calculation of speed components, the angle of attack(ϕ) on each section of the blades is obtained using polar charts available from aerodynamic simulation software (i.e. Xfoil). Knowing ϕ, the C_x and C_y coefficients (eq. 9) can be computed:

$$C_x = C_l\cos(\phi) + C_d\sin(\phi) \qquad C_y = C_l\sin(\phi) + C_d\cos(\phi). \tag{9}$$

As stated by Ning[22], it is possible to obtain tip and loss coefficients using eq.10 and eq.11:

$$f_{tip} = \frac{B}{2}\frac{(R-r)}{|sin\phi|} \qquad F_{tip} = \frac{2}{\pi}acos(e^{-f_{tip}}) \tag{10}$$

$$f_{hub} = \frac{B}{2}\frac{(r-R_{hub})}{R_{hub}|sin\phi|} \qquad F_{hub} = \frac{2}{\pi}acos(e^{-f_{hub}}), \tag{11}$$

where:

- F_{tip}: tip loss correction;
- B: blade number;
- R: rotor radius;
- r: distance from center of the rotor to root blade section;
- F_{hub}: hub loss correction.

Introducing the solidity σ as eq.12:

$$\sigma = \frac{Bc}{2\pi r}, \tag{12}$$

with c representing the chord length, then one can write eq13:

$$k = \frac{\sigma C_x}{4\sin\phi\sin\phi F} \qquad k' = \frac{\sigma C_x}{4\sin\phi\cos\phi F}, \tag{13}$$

considering $F = f_{tip}^2$. Many formulations of a are available according to the values of ϕ and k; in particular for $\phi > 0$ and $k > 2/3$ equations 14 and 15 can be used:

$$\gamma_1 = 2Fk - (\frac{10}{9} - F) \qquad \gamma_2 = 2Fk - F(\frac{4}{3} - F) \qquad \gamma_2 = 2Fk - (\frac{25}{9} - 2F) \tag{14}$$

$$a = \frac{\gamma_1 - \sqrt{\gamma_2}}{\gamma_3}. \tag{15}$$

If $\phi < 0$ and $k > 1$, the axial induction factor has the following formulation:

$$a = \frac{k}{k-1}. \tag{16}$$

Instead, if $\phi > 0$ and $k < 2/3$, one obtains

$$a = \frac{k}{k+1} \tag{17}$$

For a', a unique formulation is obtained:

$$a' = \frac{k'}{k'+1} \tag{18}$$

From the aforementioned equations, induction flow factors can be estimated in each solution region. When a turbine is yawed, otherwise, it is necessary to consider additional corrective factors: in this case the induction factor with yaw correction is eq.19:

$$a_{yaw} = a(1 + K\frac{r}{R}\sin(\psi)), \tag{19}$$

where ψ is the azimuth angle and K, from Shen[23], is given in eq20:

$$K = \frac{15}{32}\pi \tan\frac{\chi}{2}. \quad (20)$$

χ is known as skew angle and it is obtained from eq.21:

$$\chi = (0.6a + 1)\gamma \quad (21)$$

In literature, different formulations for correcting the induction factor considering yaw are available [24]. For example Coleman[25] proposed eq.22:

$$K = \tan(\frac{\chi}{2}). \quad (22)$$

For White and Blake [26] one has eq.23:

$$K = \sqrt{2}\tan(\chi). \quad (23)$$

Moreover Shen[23] proposed eq.24:

$$a_{yaw} = a\left[1 + \frac{15\pi}{32}\sqrt{\frac{1-cos\gamma}{1+cos\gamma}}\frac{r}{R}Ksin\psi\right]. \quad (24)$$

Different, additional formulations have been proposed by Ackermann [27] and Bianchi [28]. All these formulations have been compared but noticeable differences that may cause substantial changes to the algorithm have not been found.

3 Results

3.1 Analysis of Power and Thrust Coefficients

In this section, results from simulation codes and experimental measurements are shown. Figure 4 compares the measured and simulated C_p values in different yaw configurations. C_p is computed using eq. 25:

$$C_P = \frac{P}{\frac{1}{2}\rho A_{ref} U_\infty^3}, \quad (25)$$

where P is the generator power. Physically C_p measures the ratio between the power that is produced and the kinetic energy of the flow. The maximum theoretical limit of this coefficient is indicated by the Betz law [29].

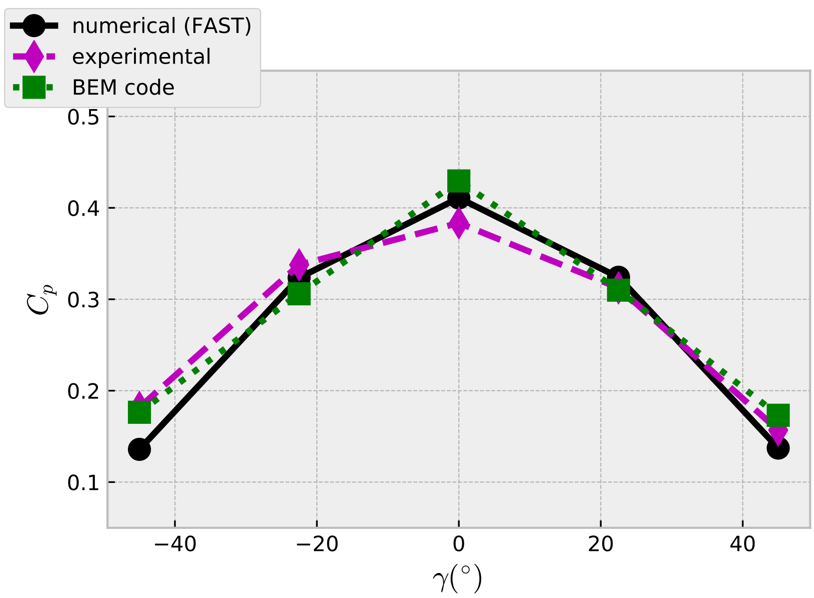

Figure 4: Power coefficients at 10 m/s: experimental vs numerical results.

Similarly to power coefficient, thrust coefficient is used to characterize turbine behavior. Its definition is given in eq.26:

$$C_T = \frac{F}{\frac{1}{2}\rho A U_\infty^2} = 4a(1-a), \tag{26}$$

where F is the thrust force acting on the rotor in the flow direction. In figure 5, the measured and simulated behavior of C_T is shown.

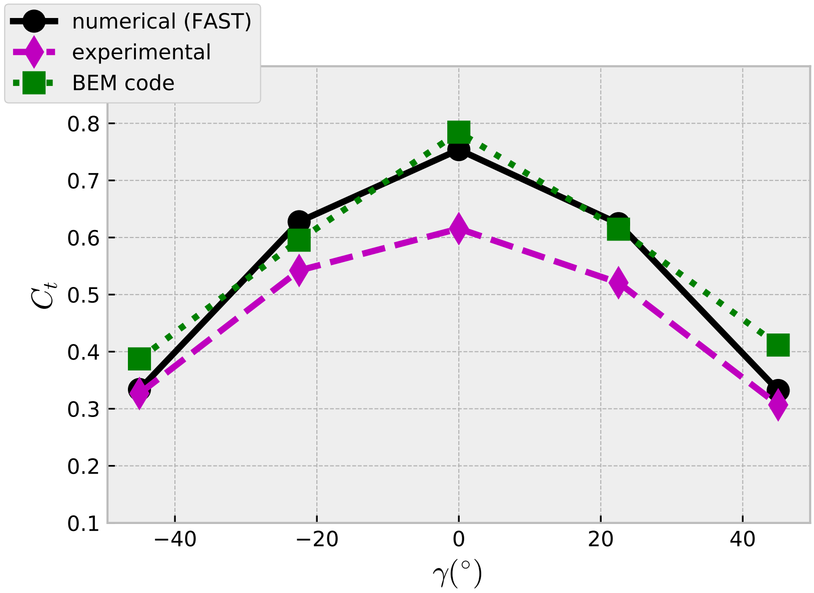

Figure 5: Thrust coefficients at 10 m/s: experimental vs numerical results.

It can be seen that both numerical models reproduce the power coefficient fairly but they largely overestimate the thrust one. The maximum percentage error for C_P is about 5% for the BEM code and 8% for FAST. In spite of this, for C_T errors are up to 25% for BEM and 20% for FAST. In numerical simulations a 95% of generator efficiency has been considered and the small errors on C_P for vanishing yaw angles shows that it can be considered a reliable estimation.

The mismatch between measured and simulated C_T coefficient can be imputable to multiple causes: the most important can be supposed to be the fact that the numerical models do not take into account blades deformations. In section 3.2, it will be discussed how the combined effects of blade deformation and tower blockage are linked to yaw configuration. In fact, the aerodynamic thrust generation depends on the distance between blade and tower in stream direction. When the turbine is yawed, this distance tends to be increased and the blades are affected by a lower tower blockage effect producing more thrust: in this case, the mismatch as regards the C_T, where blockage is not implemented, is negligible.

The slight asymmetry, visible in experimental tests, can be related to wind tunnel layout. In the open test chamber the lateral walls are placed at different distances respect the air stream and the turbine rotor. Because of this, the flow that impacts the rotor at negative or positive yaw angles is slightly different. Anyway, the discrepancies are estimated to be 3% on C_P and 8% on C_T.

3.2 Study of Thrust Cyclic Variation

Because of the critical issues revealed by the previous analysis, it has been considered useful to set up a study devoted to the cyclic variations of the aerodynamic forces during a complete rotation of a blade. The reference angle is denoted as azimuth. From Figure 6, it arises that there is periodic component in correspondence of the first blade passing frequency 3P. This phenomenon is well known and can be interpreted as due to the interaction between tower and airflow, causing cyclic decrease of aerodynamic forces. As previously explained, the intensity of the fluctuations is lower for increasing yaw angles because the blade passes farther from the low velocity air situated close to the tower.

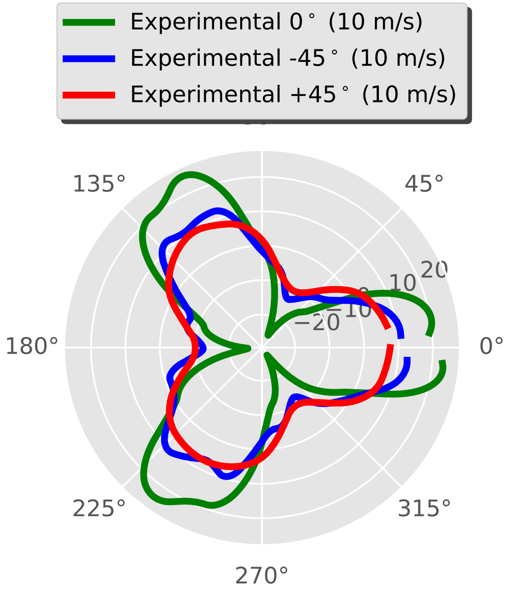

Figure 6: The rotor thrust variation(N), with respect to the average value, as a function of the azimuth angle.

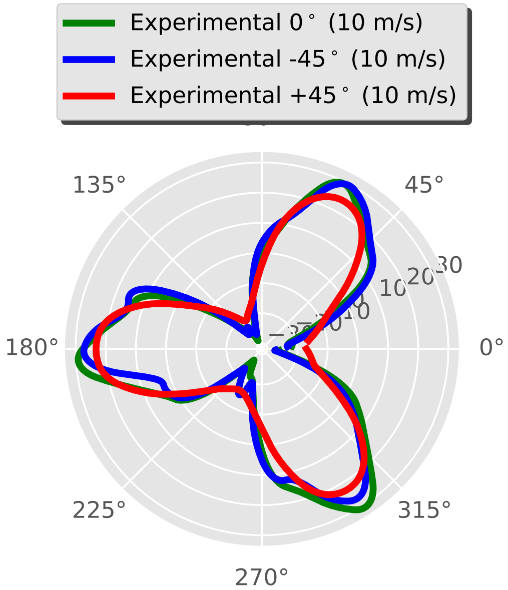

Figure 7: The rotor thrust relative variation(N), with respect to the average value, as a function of the azimuth angle.

The curves of thrust as a function of the azimuth angle have been scaled with respect to the corresponding mean value in fig. 7. It can be seen that there is a consistent overlap: this means that the amplitude of oscillations is not dependant on the yaw angle.

Additional experimental tests with a wind speed of $8m/s$ has been performed to discover the dependence of thrust oscillations with flow characteristics at 0° yaw value. The results are reported in fig. 8.

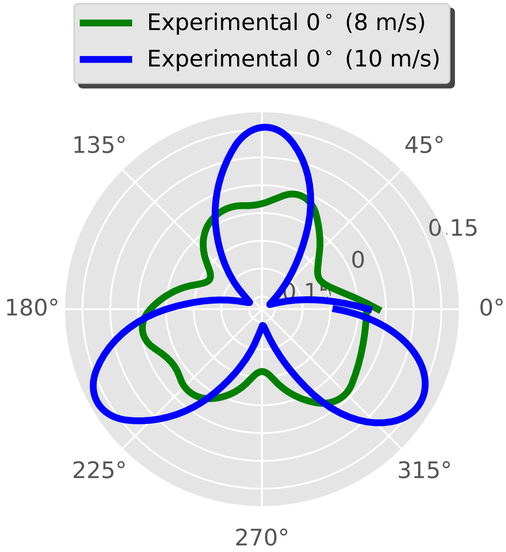

Figure 8: The rotor thrust coefficient cyclic variation in different wind tunnel tests with a wind speed of 8 m/s and 10 m/s.

From the comparison between the $10m/s$ and the $8m/s$ tests, it results that the C_T fluctuations at 10 m/s are more than doubled with respect to 8 m/s. According to this, it can be stated that the tower interference has a less relevant effect as the wind speed tends to be lower. Blade deflections in facts are strictly dependant on the aerodynamics loads and, since they decrease when the wind speed decreases, the space between the deflected blade and the tower increases and therefore the thrust is less affected by blockage. To quantify the blade deflection, it has to be considered that in previous measurements campaigns the blade deflection at the tip has been measured to be around 7% with a wind speed of $32m/s$, so it is expected that at 10 m/s it is of the order of 1% of the rotor radius: it is remarkable that this small value can induce such large tower interaction effects.

3.3 Analysis of Tower Interference on Accelerations

The above results indicate that the tower inference is a non-negligible aspect of the dynamical behavior of the small scale wind turbine considered in this study. Wind tunnel tests have been useful to deeply understand how tower interference effect gets modified by the yawing the turbine: this has been possible thanks to the triaxial accelerometer located on the nacelle, recording the aerodynamic induced vibrations. Fast Fourier Transform (FFT) theory has been used to analyze the spectrum of vibrations and making a comparison between $0°$ yaw and $+45°$, fig.9.

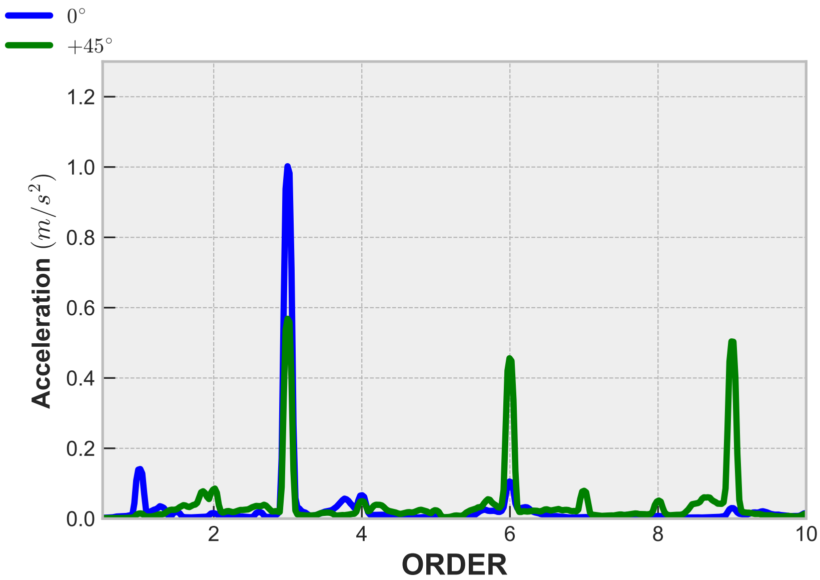

Figure 9: Experimental normalized order spectrum of the acceleration (fore-aft component normalized on the amplitude of the 3P component with zero yaw).

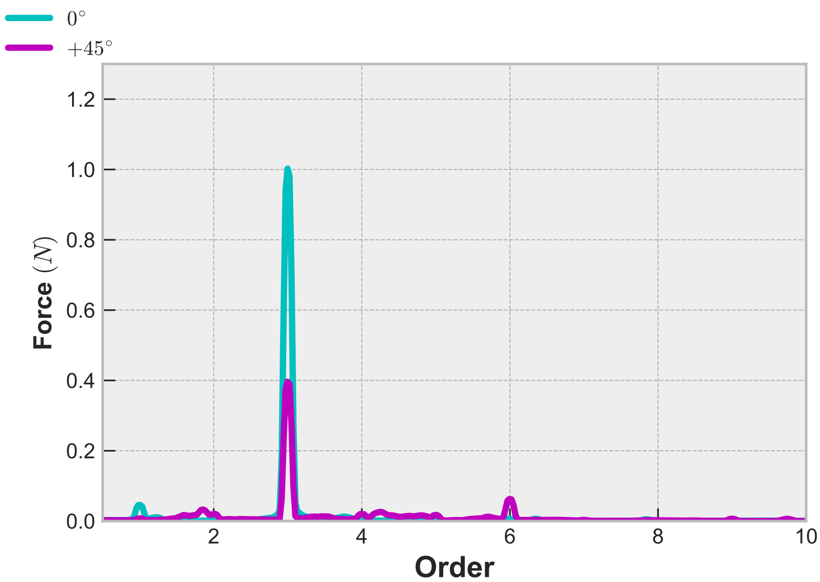

Figure 10: Experimental normalized order spectrum of the forces (fore-aft component normalized on the amplitude of the 3P component with zero yaw).

Figure 10 is the FFT of the thrust force measured by load cell placed between tower top and nacelle. Spectral analysis shows that order 3P, related to tower blockage, undergoes a substantial decrease passing from 0° yaw to 45°. This is an additional proof that gives consistency to the thesis that tower inference is more prominent for vanishing yaw angle and that justifies the thrust overestimation obtained with numerical codes, where it is not possible to account for tower blockage.

4 Conclusion

The objective of this study was the characterization of the mechanical behavior of horizontal axis wind turbines in yaw configuration. This field of study is attracting the scientific interest because yawing turbines allows several types of wind farm cooperative control, as for example the wake steering, that is useful to optimize the energy production.

A small scale horizontal axis wind turbine, with 2 m. of rotor diameter has been tested at the wind tunnel facility of the University of Perugia. The prototype has been equipped with accelerometers, load cell, electric power meter and tachometer in order to collect information about its operative conditions when undergoing different yaw angles. Experimental tests have been performed with a wind speed of 10 m/s and $\pm 45°$,$\pm 22.5°$ and $0°$ of yaw angle; additional tests have been carried out with 8 m/s of wind speed at $0°$ yaw. In addition, two numerical models have been adopted with two different software: an internally developed BEM algorithm and the open source FAST code. The numerical models have been set up in order to reproduce the conditions of the experimental test: the results are then compared in therms of power coefficient C_P and thrust coefficient C_T.

The main result is that the numerical models fairly reproduce the C_P coefficient. There are more critical points as regards the thrust coefficient: whereas for the cases of yawed configurations, the simulations fairly agreed with experimental test, for vanishing yaw angle the discrepancy is remarkable. This fact has motivated further analysis of the experimental data and the interpretation is that the mismatch between simulation and measurements is given by the fact that the tower blockage is a relevant phenomenon that the numerical models employed in this work do not take into account. The tower blockage is related to the streamwise distance between blades and tower, and so it is related to blade deflection too.

The cyclic variation of the thrust as a function of the azimuth angle has been analyzed for different yaw configurations, confirming the presence of a $3P$ periodicity which testifies the presence of a tower induced blockage effect variable respect to yaw angle. Under this circumstance an experimental test, with a wind speed of 8 m/s has been useful to confirm that with lower aerodynamic loads also the blade deflections decrease and so they do the lower thrust oscillations.

In addition, FFT analysis has been used to compare order spectra of nacelle accelerations and thrust for the $0°$ and $45°$ yaw configurations. The accelerations and thrust at 3P order appear diminished when the rotor is yawed. As this order is characteristic of tower interference effect, the order analysis brings an additional argument is support of the fact that blockage phenomenon is strictly correlated to the yawing behavior and cannot be neglected when yaw angle tends to vanish.

The results of this study can be useful to increase the knowledge of the behaviour of small wind turbines in yawed configuration and to evaluate the ability of low-fidelity numerical models predicting loads on yawed rotors. Future improvements of this study regard the possibility of better characterizing the interactions between blade tip and turbine tower, possibly using CFD codes. This study can also be useful for the implementation of wake steering wind farm control where it is expected that turbines will runs in yawed configuration for long periods and so an accurate estimation of loads is a crucial step to guarantee best performances and to assess the fatigue loading of the machine.

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