Wind Engineering Joint Usage/Research Center
FY2019 Research Result Report

Research Field: Wind Hazard Mitigation
Research Year: FY2019
Research Number:19192002
Research Theme: Wind tunnel investigation of turbulence effects on a small size Darreus wind turbine and comparisons with in-field measures

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Budget [FY2019]: Yen 400000

1. Research Aim

Small size wind turbines are becoming very popular because they can be the appropriate technology to develop the strategic aim of small-scale distributed power generation in sustainable smart cities [1]. Unfortunately, the definition of the technical data is usually obtained from wind tunnel tests without the proper attention to reproduce correctly the actual behavior in atmospheric boundary layer. Consequently, large differences are usually found between the expectations and the actual performance.
Based on the rare opportunity to have both full-scale [2, 3] and scaled experimental data on the same turbine prototype, this research aims to improve the ability of predicting the actual in-field behaviour of small Vertical-Axis Wind Turbines (VAWTs).

2. Research Method

As part of an experimental research activity, the study performs wind tunnel tests over scale models of a real VAWT, located in the Savona harbor (Italy). Two 1:10 and 1:15 scale models are designed and built, in order to have the possibility of using both the TPU and the UniGe Wind Tunnels at low blockage values (solid blockage less than 3% and total blockage, including wake effects, of around 5%). The VAWT rotor is connected by a circular shaft to a steel base where a brushed-DC motor (Figure 1.a) and the angular speed meter are located; a strain gauge allows to measure the mechanical torque. The DC motor can be deactivated and free motion tests can be also performed. The acquisition of the turbine data is managed by an Arduino system (Figure 1.a) and concerns: brake value (in %), load exerted by DC motor (in g), angular velocity of the turbine rotor (in rpm), generated power (in W). All this equipment is placed under the wind tunnel floor through a suitable horizontal end-plate. The wind velocity is measured both in the upstream and in the downstream flow (by a static-Pitot tube and a fast response anemometer, respectively). The turbulence in TPU wind tunnel is obtained by using suitable wooden grids (Fig. 1.b) whose characteristics have been deduced by a Japanese paper. The turbulence intensity obtained at the rotor level is sufficiently constant with a value of about 18% (Figure 2).
For the aerodynamics of wind turbines, the governing parameters are generally the Reynolds number, $Re=\rho UL/\mu$, and the tip speed ratio, $\lambda=\omega R/U$, where ρ and μ are the fluid density and dynamic viscosity, respectively, U is a characteristic velocity scale of the flow, L is a characteristic length scale (e.g., the radius or the chord length of the turbine), ω is the angular velocity of the turbine rotor. Considering the operational wind speed of the full-scale turbine, the Reynolds numbers tested in this study will be at least an order of magnitude lower than full-scale values, as usual for geometrically scaled models of turbines. On the other hand, the full-scale tip speed ratio can be respected in some tests since the operational maximum angular velocity of the real turbine is quite low (equal to 48 rpm). Two different procedures are adopted to obtain the experimental power curves: (1) free motion tests where, at a given wind velocity U in the wind tunnel, the turbine rotates freely (without any brake and minimizing friction) with increasing angular speed until it reaches a stationary condition (i.e., tests with increasing angular speed ω);

(2) engine-controlled tests where, at a given wind velocity U, the turbine is forced by the DC-motor to rotate at given speed ω, at the same time measuring the braking action exerted by the engine itself (i.e., tests with controlled angular speed ω). Both the procedures, carried out at different wind velocities, allow to obtain power curves Power - ω at different U.

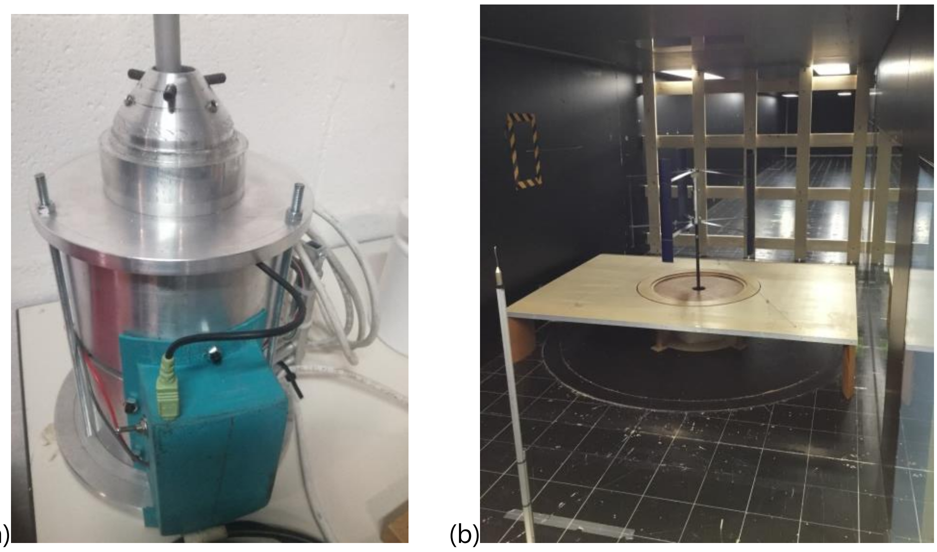

(a) (b)

Figure 1: DC-motor and Arduino system (a), 1:15 model in TPU wind tunnel with wooden grid

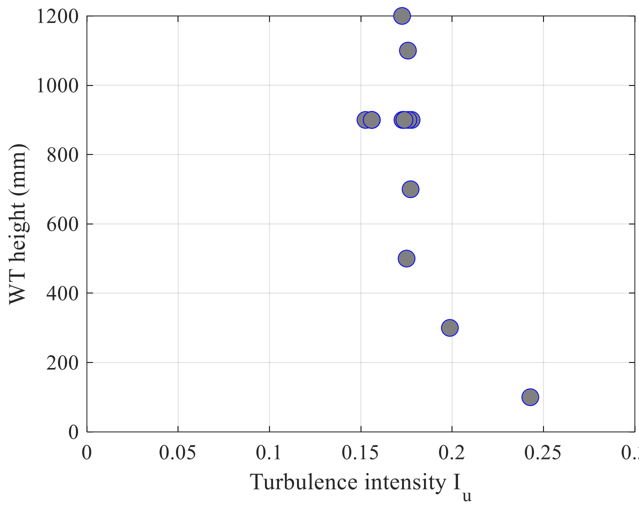


Figure 2: Turbulence intensity in the TPU wind tunnel

3. Research Result

Concerning the experimental power curves in turbulent flow, Figure 3 shows the free rotation diagrams for two different mean wind velocities in turbulent flow. In the context of Procedure 1, the experimental evolution of the angular velocity ω is first regularized by suitable spline interpolations, thus deducing an estimate of the angular acceleration $\dot{\omega}$. Then, the instantaneous power produced by the turbine P_{WT} is calculated (Figure 4) as $P_{WT} = I_{\omega} \cdot \omega \cdot \dot{\omega}$, I_{ω} being the rotational inertia.

Alternatively, in the context of Procedure 2, the turbine is forced by the DC-motor to rotate at a fixed ω-value. The generated power is obtained from the mechanical work done by the load provided by the brake in the unit of time (Figure 5). In this case, attention must be paid to the effect of the DC-motor which clearly can influence the turbine rotation. This is highlighted by

discrepancies between Figures 4 and 5, where, considering the same wind tunnel velocity, the maximum power corresponds to different angular speed in the two procedures.
In both cases the ultimate goal is to find relative maxima of the power curve as the wind speed changes in order to obtain diagrams which allow calibrating the wind turbine inverter and, therefore, to design the turbine control system.

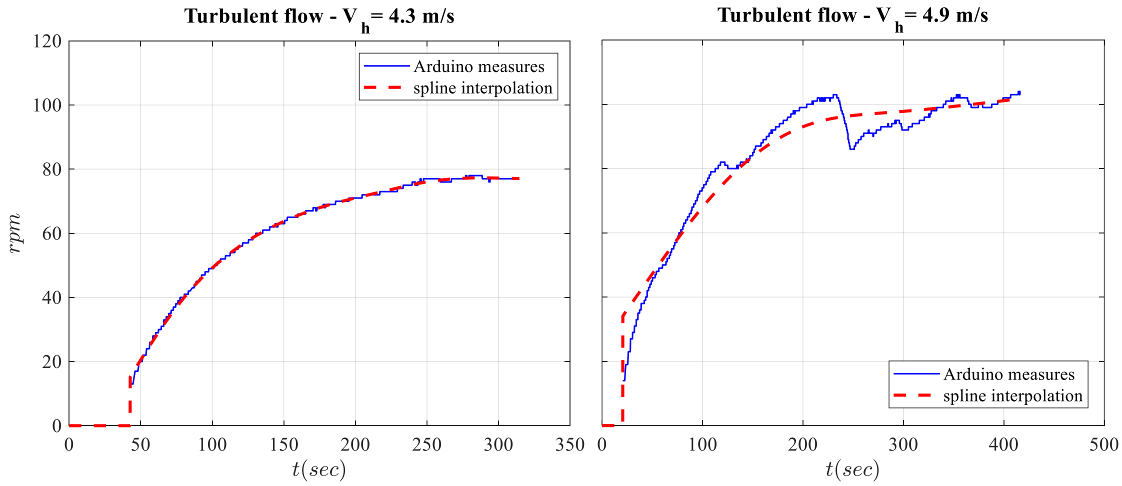


Figure 3: Experimental evolution of the angular velocity in terms of rpm for two different wind mean velocities

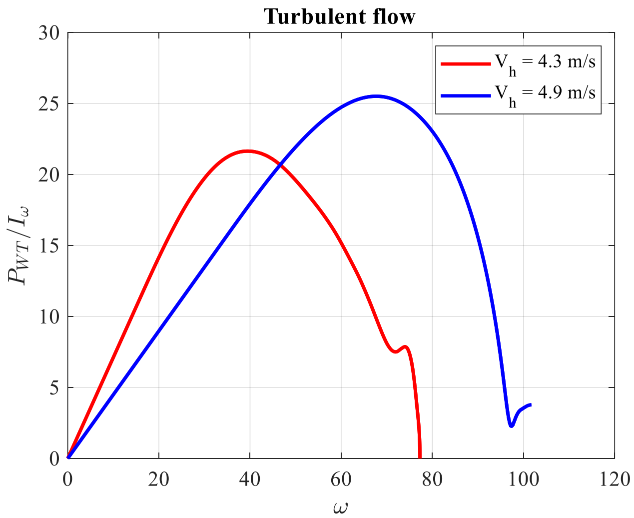


Figure 4: Estimation of the turbine production using the Procedure 1

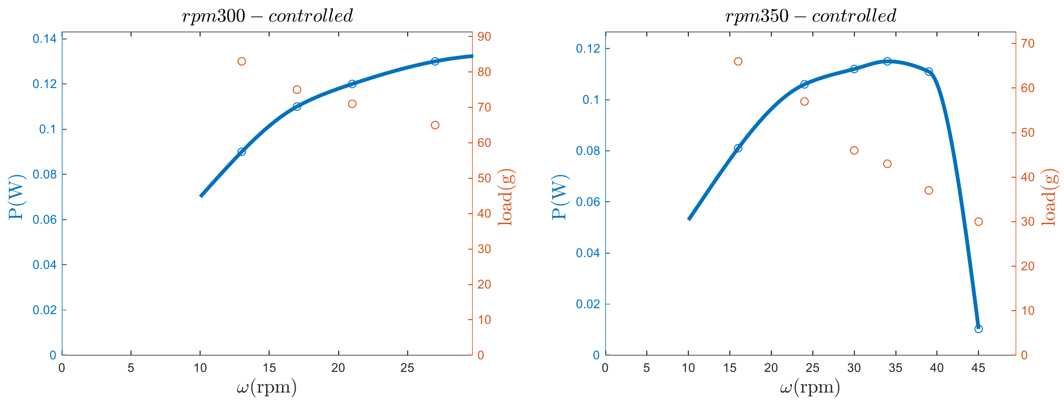


Figure 5: Estimation of the turbine production using the Procedure 2

Unfortunately, tests carried out in turbulent flow during the January 2020 campaign at TPU were affected by significant and unexpected vibrations problems of the 1:10 model, not highlighted in the current literature, which strongly affect the application of both procedures. Already for modest flow velocities in the wind tunnel, as the velocity increases (over TPU wind tunnel 350 rpm, corresponding to a mean velocity of about 5 m/s), the turbine model has shown significant vibrations that have heavily influenced the rotation of the turbine itself (see, for instance, Figure 6). The increase in rotation during free turbine motion is no longer gradual: a sudden increase in rotation speed occurs in a very short time (few seconds). This seems attributable to resonance phenomena between the rotation speed and the shaft supporting the turbine rotor. An almost clear resonant vibration appears at about ω=150 rpm.

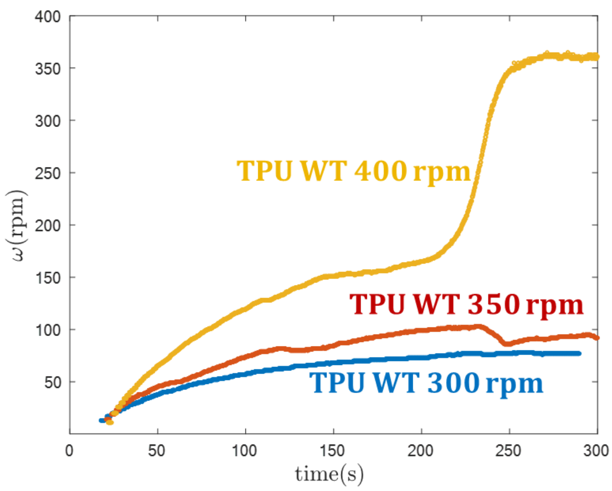
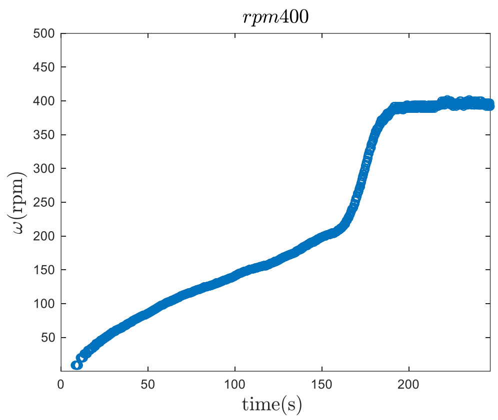


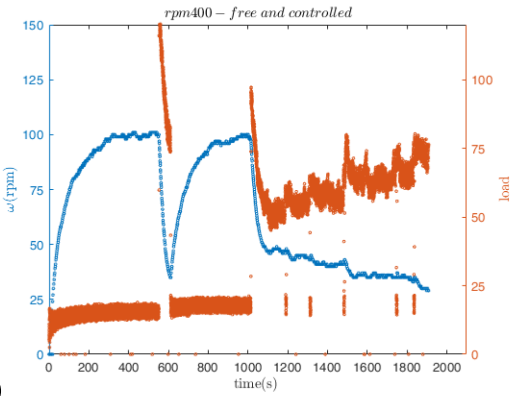
Figure 6: Experimental evolution of the angular velocity ω as the WT flow speed changes

All attempts made to improve the setup by stiffening the shaft with suitable tie wires (in rope or steel) have unfortunately not led to the desired results (Figure 7). Using rope wires the model is stiffer but the resonant vibrations shift to about ω=200 rpm (Figure 7.a). The effect of steel wires initially seemed positive (Figure 7.b), even if the behavior looks very different from tests without stiffening; but, also in this case, the problem is only translated at slightly higher flow velocities (Figure 7.c).
Finally, during the last day in TPU, we removed the wooden grid to perform comparative tests in smooth flow conditions. Now the situation appears completely different in terms of flow velocity and corresponding turbine response. Up to 700 rpm of TPU Wind Tunnel, the turbine rotor turns very slowly (hardly exceeds 60 rpm). At 800 rpm of TPU Wind Tunnel in smooth flow conditions (Figure 8), the turbine behavior is similar to what happened at 350 rpm in turbulent conditions (therefore with a velocity more than doubled). Figure 9 shows the turbine angular

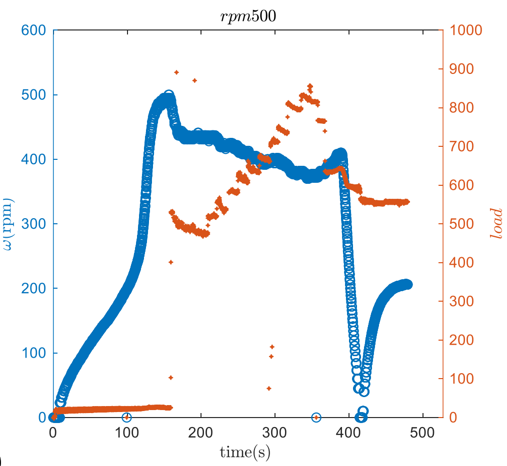
rotation in free and controlled tests at 900 rpm of TPU Wind Tunnel, showing a regular behavior. The last test was performed at the maximum TPU wind tunnel velocity, equal to 950 rpm. Figure 10 concerns free turbine evolution (Figure 10.a) and the corresponding power production through Procedure 1 (Figure 10.b). Figure 11 shows the controlled tests with an evaluation of the turbine production by Procedure 2 (Figure 11.b). Comparing Figures 10 and 11, remarkable differences still persist concerning the optimal rotation value (at the same flow velocity) obtained by the two procedures. This deserves further investigations, appropriately taking into consideration the suitable calibration of the DC motor.



(a)



(b)



(c)

Figure 7: Experimental evolution of the angular velocity ω for different shaft stiffening systems

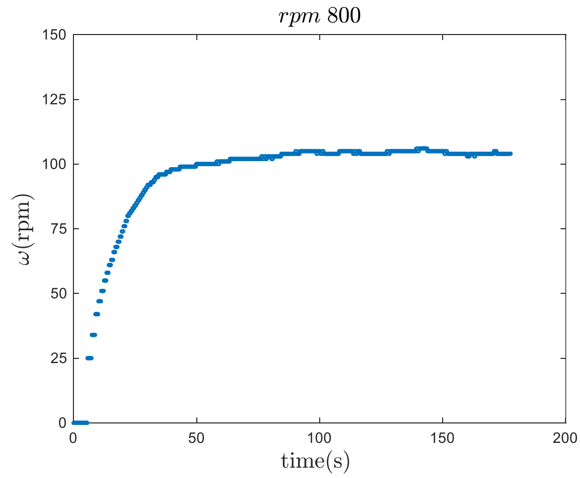


Figure 8: Experimental evolution of the rotor angular velocity ω at 800 rpm wind tunnel velocity in smooth flow conditions

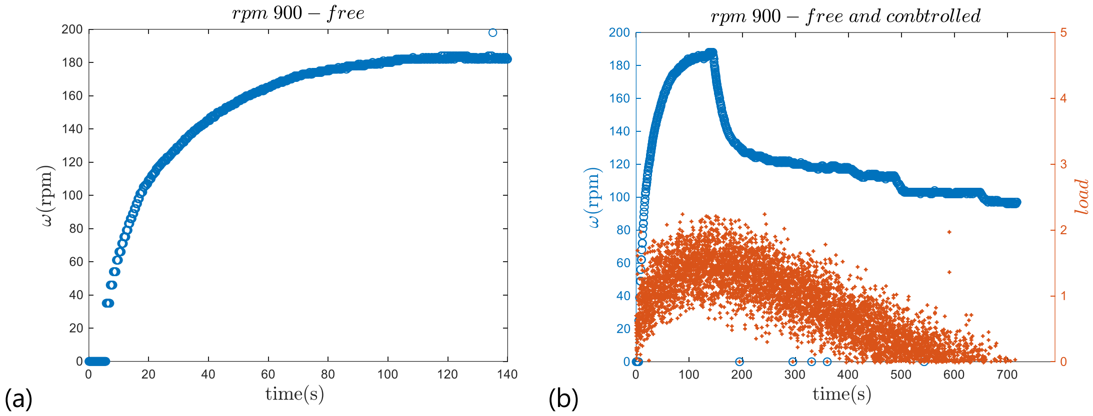


Figure 9: Experimental evolution of the angular velocity in free (a) and controlled motion (b) at 900 rpm wind tunnel velocity

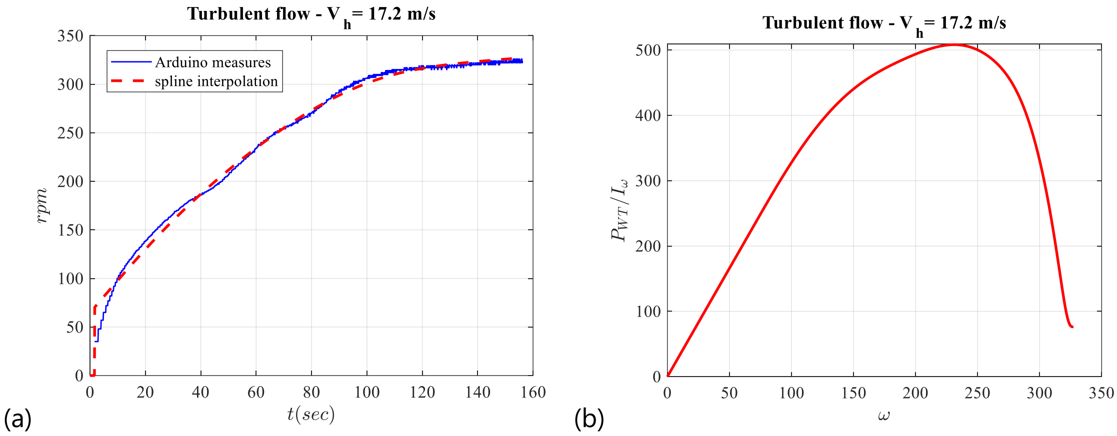


Figure 10: Experimental evolution of the angular velocity for free test (a) and estimation of the corresponding turbine production using the Procedure 1 (b)

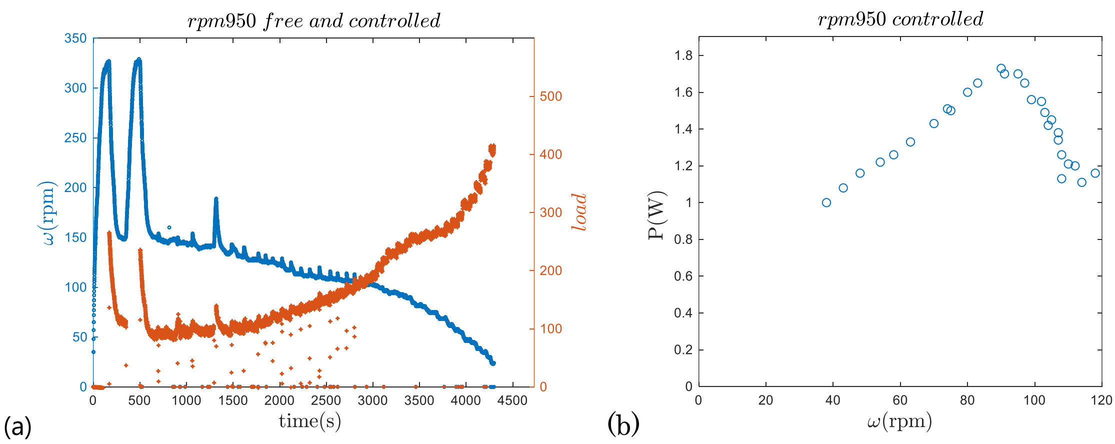


Figure 11: Experimental evolution of the angular velocity for free and controlled test (a) and estimation of the corresponding turbine production using the Procedure 2 (b)

Final remarks

This research represents an almost unique case in the literature on VAWTs, having the possibility to measure the same prototype both in full scale conditions and properly scaled in two different wind tunnels (therefore also investigating Reynolds effect and tip speed ratio influence). The results presented in this activity report are the very first phase of the research, preliminary but absolutely necessary to highlight a series of problems that need to be examined one by one for subsequent scientific purposes. However, three points are noteworthy as of now:

(1) results obtained in the case of turbulent flow are considerably different from those in smooth flow. This outcome, supported by full scale measurements, differs significantly from the recent literature on the subject. Power curves obtained by Carbó Molina et al. [4] do not show substantial differences from each others when turbulence intensity varies in the range 0.7-14.8%. Especially, they find a remarkable increase in the power production with the turbulence level. Our results show a very different behavior in the presence of turbulence. Considering that the optimization of VAWTs is commonly based on smooth flow tests only, these findings justify the large detrimental effect of turbulence on the full scale performance often detected in small size wind turbines and, in particular, in the investigated turbine;

(2) turbulent flow tests also highlight significant problems with increasing rotational speed due to resonance vibrations of the shaft supporting the rotor. These problems need to be addressed for a complete investigation of the power curve;

(3) unlike what is usually done, the power curves have been obtained with two different procedures. The Procedure 1 (which uses the free turbine motion, completely decoupled from the DC motor) is not detailed by the scientific literature. At least in principle, it is probably the most correct procedure. However, comparisons with the results obtained by Procedure 2 are still to be explored.

References

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[3] L.C. Pagnini, G. Piccardo, M.P. Repetto, “Full scale behavior of a small size vertical axis wind turbine”, Renew. Energy, 127 (2018).

[4] A.C. Molina, T. De Troyer, T. Massai, A. Vergaerde, M.C. Runacres, G. Bartoli, “Effect of turbulence on the performance of VAWTs: An experimental study in two different wind tunnels”, J. Wind Eng. Ind. Aerodyn., 193 (2019)

4. Published Paper

Freda, A., Pagnini, L., Piccardo, G., Bissanti, R., Yoshida, A. (2020). Full-scale and scaled experimental studies on a small-size vertical-axis wind turbine. Extended abstract accepted for presentation at 9th International Colloquium on Bluff Body Aerodynamics and Applications (BBAA IX), University of Birmingham, UK, 20 - 23 July 2020 (postponed to 2021 due to covid-19)

5. Research Group

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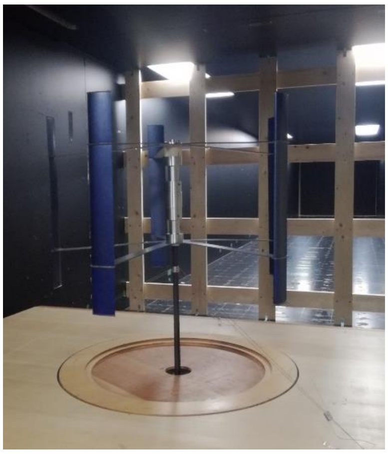
   Akihito Yoshida

2. Collaborate Researchers
   Andrea Freda

6. Abstract (half page)

Research Theme: Wind tunnel investigation of turbulence effects on a small size Darreus wind turbine and comparisons with in-field measures
Representative Researcher: Luisa Pagnini, Giuseppe Piccardo (University of Genoa)

Small size Vertical-Axis Wind Turbines (VAWTs) represent a very interesting technological alternative for a distributed power generation from smart city viewpoint too. However, there are still large differences between expected and real performances, especially when the wind flow is very turbulent. On the contrary, some recent scientific papers through wind tunnel results seem to highlight a beneficial effect of the turbulent action.
Based on the rare opportunity to have both full-scale and scaled experimental data on the same turbine prototype, the present research intends to make a first contribution to bridge the gap between theoretical and real expectations in small size energy production.
Wind tunnel tests over scale models of a real VAWT, located in the Savona harbor (Italy) are carried out. Two 1:10 and 1:15 scale models are realized, in order to have the possibility of using both the TPU and the UniGe Wind Tunnels at low blockage values (solid blockage less than 3% and total blockage, including wake effects, around 5%). The turbulence intensity obtained at the rotor level in the TPU facility is about 18%. Two different procedures are adopted to obtain the experimental power curves: free motion tests where, at a given wind velocity, the turbine rotates freely with increasing angular speed until it reaches a stationary condition, and engine-controlled tests where the turbine is forced by the DC-motor to rotate at fixed angular speed.



The first phase of the research highlights a series of problems but, at the same time, points out some results not in accordance with recent literature on this topic. In particular, for a fixed value of the mean flow velocity, the behavior in the presence of turbulence looks completely different from the behavior in smooth flow. Considering that the optimization of small size VAWTs is commonly based on smooth flow tests only, these findings justify the detrimental effect of turbulence on the full scale performance often detected in this kind of systems and, in particular, in the investigated turbine.