20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Wind turbine vibration monitoring based on finite-element (FE) simulation

Marcantonio Catelani[1], Lorenzo Ciani[1], Susanna Papini[2], Andrea Rindi[2]

[1]*DINFO, Dept.of Information Engineering, University of Florence, Via di Santa Marta 3, 50139, Firenze, Italy; lorenzo.ciani@unifi.it*
[2]*DIEF, Dept. of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139, Firenze, Italy; andrea.rindi@unifi.it*

Abstract **– The design of wind turbines evolved over time, with the scope of becoming less expensive and producing energy more efficiently. This paper deals with a FEM model for the representation of vertical axis wind turbine (VAWT) functioning for diagnostic and monitoring studies, which can provide fundamental data that can optimize the design of the monitoring system and an improvements in fault diagnosis related to vibration effects. In particular in this paper will discuss a monodimensional VAWT model, in order to reduce the computational time and, at the same, by using low computational resources to analyze several load cases. Growing usage of wind turbines has made maintenance a priority, and diagnosing potential faults is crucial to maintaining the turbineś desired availability. The simulation data obtained by the proposed approach allows to optimize condition monitoring and fault diagnostic techniques by the analysis of the wind turbine behavior before the real use on the field with both time and costs reduction.**

I. INTRODUCTION

In recent years there has been a pick up in H-type Darrieus vertical axis wind turbine (VAWT) interest, especially for urban-scale applications. VAWTs have some advantages over horizontal axis machines (HAWT) like their low visual impact and the lower noise production.

Actually the production of small wind turbine is just at handmade level, and the materials most used are mainly steel or aluminium alloys, [1] [2]. Therefore with the goal to reduce the cost of the machines some firms decide to industrialize the production using different materials (e.g. plastic or light alloys). Using these materials the stress calculation in different load cases become mandatory, because of their tensile stress is very low. [3], [4].

In this article a monodimesional model is presented, in order to reduce the computational time also with low computational resources, for analyse many load cases. The microturbine was modelled with beam elements.

The 1D structural model is used to verify the dynamic response of the wind turbine in real functioning condition with GAROS software for different study cases, and some test indicated by the $IEC61400 - 2Standard$, [5]. By means of the proposed model it is possible to optimize the condition monitoring and fault diagnostic techniques before the real use in the field[6]. Many operators employ periodic inspections for condition assessment based on empirical and subjective measures [7]. Such inspections are generally expensive and often intrusive and require undesired scheduled downtime [8], [9],[10]. Instead, the proposed approach allows to obtain a cost reduction due to the possibility to simulate ahead the VAWT functioning behavior.

The paper is organized as follows: in Section II the wind turbine FEM model is described and validated; in Section III the aeroelastic analysis results are discussed in detail. Finally, conclusions are presented in Section IV.

II. TURBINE FEM MODEL

The test case is a 900 W turbine [11] which has three twisted blades derived by a Darrieus vawt with a total swept area of 2.1 m^2, it is pictured in Figure 1. The maximum design wind speed is 15 m/s and rated at 415 rpm.

The blades of the turbine have a very curved geometry especially on the bend, on blades' surfaces there are several stiffening ribs, moreover on the blades are screwed some roofing that allow the blades to have airfoil sections. These roofing are very thin and don't give any more stiffening to the blades.

Each blade is made up by two part, linked to the central pole by means of two beams with C section on the top and bottom; another beam is located in the middle of the blade with rectangular section but with width not constant along its axis.

Beam elements are selected for the model, as they are one-dimensional elements with 6 dof for each node. So this modelling plan allowes a short computing times [13], [14].

For the definition of each element are necessary: the position of the nodes and the inertial property of each section. The presence of the stiffening rib on the blades surfaces and the airfoil for of each section cause the position of the

ISBN-14: 978-92-990073-2-7

shear centre out of the profile. Moreover the shear centres are not aligned. So for each node it is necessary to calculate an appropriate offset to locate the sections on the right positions.

For the inertia property of the section it was necessary to slice the blades and then calculate it for each section, like: area, moment of inertia, centre of gravity, torsional stiffness and shear centre.

In order to evaluate the performances of the model, the static and dynamic results are compared with the ones obtained by a model created with shell elements (more accurate). For an initial stress comparison it is necessary to insert the position of stress data recovery on the beam property. These positions are selected like the most critical stiffening ribs, trailing and leading edge of the blades. The critical stiffening ribs are selected using the shell model.

Therefore it will be obvious that the preprocessing is very long, because for each section it is necessary calculate: the section inertia property, stress data recovery positions and the shear centre positions.

Finally also the roofings was modelled because they are realized with the same materials of the blade, these components are modelled like non structural masses.

So also if they don't give any more stiffening at the structure, they increase the centrifugal forces, moreover the position of the roofings are quit far from the revolution axis, so their centrifugal force contributions are not unimportant. So in the property of the beam element are inserted the values of non structural masses calculated like the ratio between total mass of the roofing and the length of the blade.

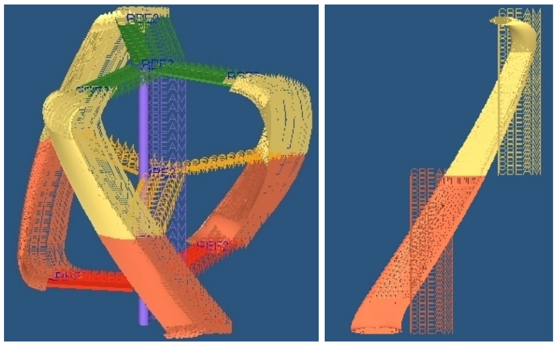
All the connection with bolts on the turbine are modelled with rigid elements, beeing the material used for the blades is polypropylene and the one for the bolts is steel, so there is a very height difference of stiffening. Therefore modelling bolts with rigid elements don't introduce significant errors. Instead, the connection between the beams and the central pole are modelled with beam element with the steel property. On the turbine the connection are made by bolts on flange all in steel. Using rigid elements give too much stiffness to the structure. The Figure 2 report some details of FEM model, respectively the whole turbine and blade's particular.

A. Model validation

Using beam elements for geometry so curved and not linear could introduce errors in static and dynamic response. So a static analysis under a centrifugal field is performed on beam and shell models. The centrifugal field is input by a rotary speed of 415 rpm. It was decided to compare the trends and values of the stress, because the stress is the main value for the determination of the failure.

In order to evaluate the quantitative static response too,

Figure 1. An VAWT turbine.



a) b)

Figure 2. 1D FEM model of turbine and blade's detail.

the nodes values in the same position for the shell and the beam model.

The stress-strain results were compared calculating at different spans the absolute VM-stress values and the percentage error between the models using following equation, where *beam* and *shell* subscript are referred to bi-dimensional and mono-dimensional case respectively:

$$\varepsilon = \frac{|\sigma_{shell} - \sigma_{beam}|}{\sigma_{shell}} \cdot 100 \qquad (1)$$

The table 1 resumes the stress for these nodes and the percent error. It can be noted that there is good agreement between the calculated stress values for both FEM models, with maximum calculated stresses of a maximum stress of 56.7 MPa for the beam model and 59.4 MPa for the shell model, and also with a maximum error of less than 7% and an average error in the order of 3%.
For structure which rotate it is very important its dynamic response. So it was estimate the quality of the dynamic results with modal analysis locking the bottom of the pole on frequency 0÷20 Hz range.

On the other hand quantitatively are calculated the percent errors of the mode frequencies similarly at static vali-

Table 1. Static analysis comparison between 1D and 2D stresses.

ID node	Beam stress [MPa]	Shell stress [MPa]	error %
124	33.51	34.72	3.49
132	12.30	13.19	6.75
290	50.50	53.27	5.20
460	43.88	45.51	3.58
471	51.73	49.89	3.69
479	34.90	35.17	0.77
551	22.53	22.83	1.31
610	39.54	41.16	3.94
719	25.27	25.52	0.98
731	11.64	12.01	3.08

Table 2. Dynamic analysis comparison between 1D and 2D frequency.

Eigen mode	Beam frequency [Hz]	Shell frequency [Hz]	error %
1	7.95	7.85	1.27
2	15.1	13.9	8.63
4	15.7	16.1	2.48
5	22.8	23.2	1.72
7	25.4	25.7	1.17

dation. The table 2 resumes the frequencies for each mode and the percent errors. Also in this case the agreement between the FEM models is appreciable, the types of vibrations mode are substantially the same. The first vibration modes, i.e. the most critical ones, have an percent error little bit higher than expectations, in particular the thirdone, but the absolute error is only 2.2 Hz, which is definitely a good result if one considers the approximation introduced by the beam model.

After the results analysis it is possible to claim that the behaviour of the models are the same. Indeed the trend of displacement and stress are the same, the modes are the same and the percent errors are very low (under 10%) for both stress and frequencies values.

III. AEROELASTIC ANALYSIS RESULTS

The aeroelastic behavior was carried out with GAROS software for different operating conditions according to $IEC\ 61400-2$ [5]. GAROS is a program by AeroFEM GmbH; it's for the aeroelastic-and rotordynamic analysis of wind turbines. Stability and dynamic response in time domain analysis can be done. Both horizontal and vertical axis turbines can be analysed. The program is based on a modal coupling method of tower and rotor. The structures are idealised by finite monodimensional elements. The subroutine for modal analysis contains the fully coupled rotor dynamic matrices, including the geometric stiffness matrix. In the stability analysis, the quasi steady linearized aerodynamic stiffness, damping and mass matrices are considered.

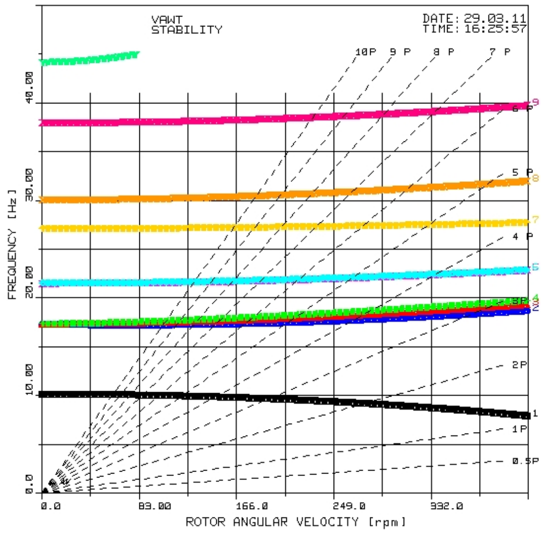


Figure 3. GAROS results: Campbell diagram without aerodynamic forces.

The static deformation of the blades can be accounted for in order to calculate the stability behavior at different operating conditions. The GAROS software produces the Campbell diagram for the structure behavior in function of rotor velocity without and with aerodynamic forces. Figure 3 and Figure 4 show the Campbell diagrams without and with aerodynamics loads respectively. It is possible to note that the vibration modes are independent from the rotational speed when $\omega > 160\ rpm$. In case of mechanical loads only, no instabilities are noticed in the operating range of the turbine. The aeroaerodynamic loads condition the relationship between the vibrational modes and rotor speed. In particular the aerodynamics make worse the structure's stability, as the natural frequencies are shifted towards the excitations of the system. The absence of predicted instabilities of the system has been positive for the structural integrity of the rotor, even if proper experimental verifications are needed.

In addition to the stability analysis, dynamic response analysis can also be investigated; to weigh the potential offered by this new software and verify beam model the response to a wind variation of turbine was estimated. The model considered the structural response in term of displacement of a node at middle-span of an half blade for a ramp wind variation, it is shown in Figure 5. As predicted, the displacements amplitude follow the wind speed behavior, due to the different intensity between aerodynamic forces. In accordance with as required by the IEC 61400-2 Standard, the GAROS software [12]. was exploited to va-

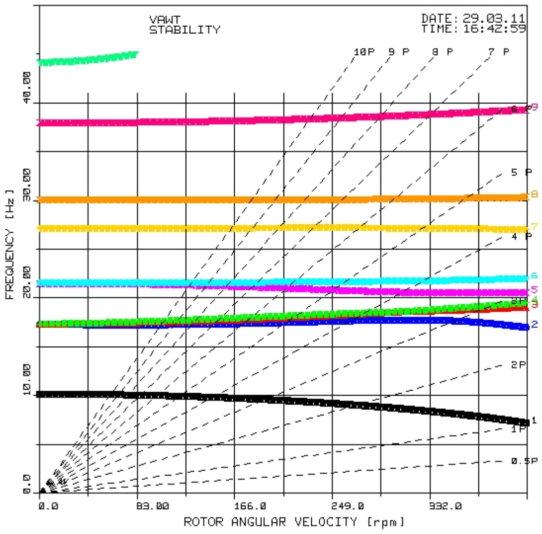


Figure 4. GAROS results: Campbell diagram with aerodynamics.

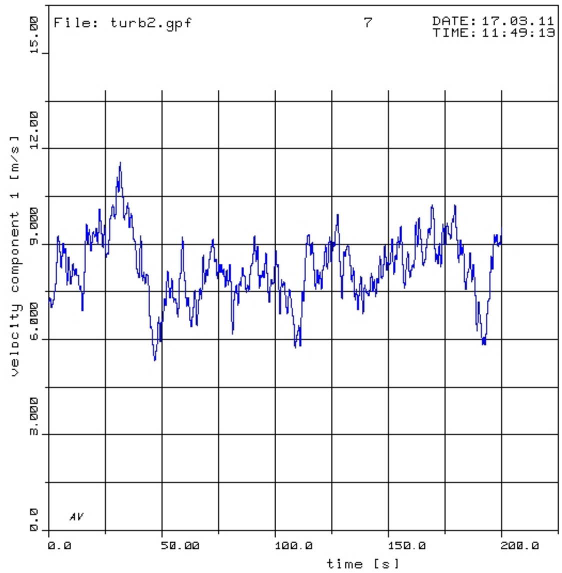


Figure 6. Turbolence timehistory.

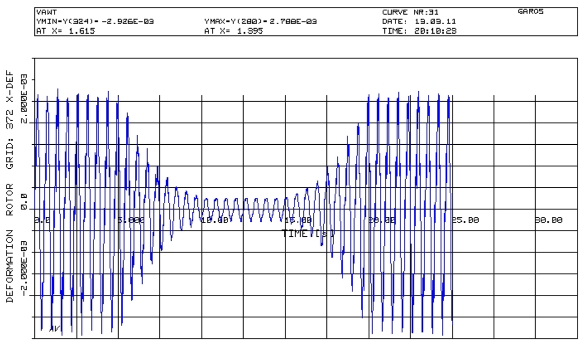


Figure 5. Nodal displacement of rotor due to a ramp wind.

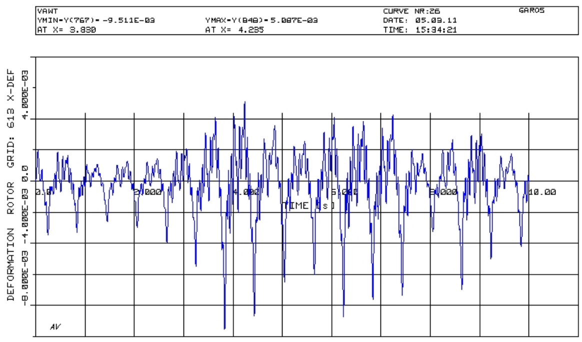


Figure 7. Nodal displacement of rotor due to a turbulent wind.

lutate the response of the turbine to wind with a given turbulence in terms of intensity and power spectrum [5]. In Figure 6 is presented the oncoming wind and in Figure 7 is shown the turbine's response. A strongly turbulent wind has a notable impact on the structural behavior of a rotor like the one investigated in this study, whose light material induces notable deformations.

The proposed procedure can predict the turbine behavior under the majority of load cases imposed by the standard IEC. Even if the 1D model appears greater rigidity about maximum values of strain, the obtained results are satisfactory, the percentage error in 1D model are comparable to 2D model. The powerful gain is that 1D model of the rotor allowed reducing the total degrees of freedom of the structure to 6084 from the original number of 751965 for the 2D shell model.

IV. CONCLUSIONS

This paper reports a simplified model for the evaluation of the structural response. In particular it was modelled a small VAWT with beam elements. It allows to calculate global stress of the structure and the deformed shape under load cases. The results show that the main stress is caused by the centrifugal forces generated by the rotation of the machine; the aerodynamic forces give a second order contribution. The 1D model was then set to fulfill the requirements of the GAROS software, which allows an aeroelastic analysis of the Darrieus turbines. The software was tested in some study cases, including some test indicated by the IEC 61400-2 Standard, obtaining a very good agreement with theoretical expectations.

The proposed modeling ensures a notable reduction of the calculation resources in comparison to more sophisticated techniques. This topic is becoming more and more important as the number of installed turbines increases. So, it represents an interesting tool for industrial manufacturers who want to effectively design and verify their models.

Finally, the wind turbine simulation results allow to optimize, in terms of time and costs, the condition monitoring and fault diagnosis approach. In fact, by means of such data a new maintenance strategy may be define with the condition monitoring of critical components [15] that represents an important measure for predictive maintenance and condition based maintenance of wind turbine operation. A future development of this study will be address to compare the simulation results also with real measurements. In this new step will be put in evidence the impact of uncertainties in the proposed method.

REFERENCES

[1] Bianchini, A., Ferrara, G., Ferrari, L. and Magnani, S., " An improved model for the performance estimation of an H-Darrieus wind turbine in skewed flow", Wind Engineering, 36(6), pp. 667-686.

[2] Balduzzi, F., Bianchini, A., Carnevale, E.A., Ferrari, L. and Magnani, S., 2012, "Feasibility analysis of a Darrieus vertical axis wind turbine installation in the rooftop of a building", Applied Energy 97, pp. 921-929.

[3] Bianchini, A., Ferrari, L. and Magnani, S., "Energy-yield-based optimization of an H-Darrieus wind turbine", Proceedings of the ASME Turbo Expo 2012, Copenhagen, Denmark June 11-15, 2012.

[4] Bianchini, A., Cangioli, F., Papini, S., Rindi, A., Carnevale, E.A. and Ferrari, L., "Structural analysis of a small H-Darrieus wind turbine using beam models: development and assessment", Proceedings of the ASME Turbo Expo 2014, Dusseldorf (Germany), June 16-20, 2014.

[5] "IEC 61400-2. Design requirements for small wind turbines", International Standard, second edition, 2006.

[6] Loredana Cristaldi, Marco Faifer, Massimo Lazzaroni, Mohamed Mahmoud Abdel Fattah Khalil, Marcantonio Catelani, Lorenzo Ciani , "Failure Modes Analysis and Diagnostic Architecture for Photovoltaic Plants", Proc of 13th IMEKO TC10 Workshop on Technical Diagnostics, "Advanced measurement tools in technical diagnostics for systems reliability and safety", June 26-27, 2014, Warsaw, Poland, pp. 206-211.

[7] Adam Jablonski, Tomasz Barszcz, Marzena Bielecka, "Automatic validation of vibration signals in wind farm distributed monitoring systems", Measurement, Volume 44, Issue 10, December 2011, Pages 1954-1967, ISSN 0263-2241, http://dx.doi.org/10.1016/j.measurement.2011.08.017.

[8] Bin Lu, Yaoyu Li, Xin Wu, Yang, Z.,"A review of recent advances in wind turbine condition monitoring and fault diagnosis", 2009, PEMWA-Power Electronics and Machines in Wind Applications, . IEEE , vol., no., pp.1,7, 24-26 June 2009, doi: 10.1109/PEMWA.2009.5208325.

[9] E. Echavarria, B. Hahn, G. J. van Bussel, T. Tomiyama, "Reliability of Wind Turbine Technology Through Time", Journal of Solar Energy Engineering 2008, Transactions of the ASME 031005-8 / Vol. 130, AUGUST 2008

[10] Lin Bo, Xiaofeng Liu, Xingxi He, "Measurement system for wind turbines noises assessment based on LabVIEW", Measurement, Volume 44, Issue 2, February 2011, Pages 445-453, ISSN 0263-2241, http://dx.doi.org/10.1016/j.measurement.2010.11.007.

[11] Pramac SpA,"WT1kW Use and Maintenance Manual", downloaded from: http://www.navitron.org.uk.

[12] AeroFEM GmbH, 2012, "GAROS Software Presentation, tech. rep.", downloaded from: http://www.aerofem.com.

[13] O.C. Zienkiewicz and R.L. Taylor, "The Finite Element Method for Solid and Structural Mechanics", Elsevier, sixth edition, 2005.

[14] Hughes, T.J.R., 1987, "The Finite Element Method: Linear Static And Dynamic Finite Element Analysis", Dover Publications, USA.

[15] Marcantonio Catelani, Lorenzo Ciani, Loredana Cristaldi, Marco Faifer, Massimo Lazzaroni, "Electrical performances optimization of Photovoltaic Modules with FMECA approach", Measurement, Volume 46, Issue 10, December 2013, Pages 3898-3909, ISSN 0263-2241, http://dx.doi.org/10.1016/j.measurement.2013.08.003.