A XV-a Conferinţă internaţională – multidisciplinară
„Profesorul Dorin Pavel – fondatorul hidroenergeticii româneşti"
SEBEŞ, 2015

CONSIDERAŢII PRIVIND ANALIZA STRUCTURAL-DINAMICĂ PENTRU O TURBINĂ EOLIANĂ DE MICĂ PUTERE CU AX VERTICAL

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CONSIDERATIONS ON THE DYNAMIC STRUCTURAL DESIGN FOR A SMALL POWER VERTICAL AXIS WIND TURBINE

The paper presents the main aspects regarding the dynamic structural design for a small power vertical axis wind turbine. The research is applied to a 3-bladed, Darrieus type, small power, vertical axis wind turbine installed on a self-standing pole. First the main sources for the dynamic forces acting on the structure are described. Then a complete investigation on the turbine structural response is done, performing a modal analysis applied to the single rotor, considering several rotational speeds. Next, taking into consideration a building integrated wind turbine, the system composed by the turbine rotor and the mast is investigated. Finally, a thorough discussion of the main implementation problems and design alternatives is presented for a building integrated wind turbine.

Keyword: small power vertical axis wind turbines, modal analysis, Campbell diagram, urban implementation

Cuvinte cheie: analiză modală, turbine eoliene de mică putere cu ax vertical, implementare urbană, diagrama Campbell

1. Introduction

Renewable energies are one of the main subjects of research today, continuously aiming to bring better solutions and improved efficiency. These targets apply also for wind energy sector.

Wind energy technologies have two main development directions: large wind turbines (onshore and offshore) and small wind turbines (mainly onshore, with an increasing interest for the built environment application), each one coming with its design challenges. In this paper the aspects regarding small power wind turbines implementation in the urban environment will be investigated.

From several studies, the main problems raised by the built environment (mainly urban one) have been underlined: low wind speeds, gusty wind, high level of turbulences, sudden changes in wind speed or direction, emitted noise and vibrations transmitted to the supporting structure [1].

There are two main types of wind turbines: horizontal axis and vertical axis [2]. Considering the above mentioned problems of the urban environment, in [1], the advantages and disadvantages of the two wind turbines types are presented. Hence, the one proven more suitable for urban environment is the vertical axis ones, due to its better capacity to work in turbulent flow conditions and its ability to take up wind from any direction, also with skewed flows.

The most encountered research regarding small wind turbines is the improvement of aerodynamic performance, sometimes neglecting the influence of the turbine on the building. Hence, in this article we are focusing on the problem of the dynamic structural design of the implemented wind turbine into the building structure, by analysing the natural mode shapes and the mode shapes during operation, at different rotational speeds.

2. Purpose of the research

The design of small power wind turbines aims to minimize the energy production cost by: increasing the energy harvest and reducing the turbine cost. The first part is focusing on the following, maximizing for the target site with a given root mean cube wind speed V_{rmc}:

1) the rotor swept area $\boldsymbol{A}$;

2) the average aerodynamic efficiency of the rotor $\boldsymbol{C_P}$;

3) the energy conversion efficiency of the electromechanical drive train (considering also the rotor control strategy) $\boldsymbol{\eta_{elm}}$;

$$\boldsymbol{P_{el}} = \frac{1}{2}\rho {V_{rmc}}^3 \boldsymbol{A C_P \eta_{elm}}$$

The second part is done by minimizing:

1) the material cost of the turbine, without compromising the structural safety of the turbine;

2) the generator and electrical equipment cost.

3) the installation and the support structure cost.

Some constrains are the produced noise and also the transmitted vibrations to the structure on which is mounted. All these must be reduced by considering that the efficiency of the turbine remains unchanged.

In order to achieve these objectives, a dynamic structural design with a modal analysis of the system is fundamental. In literature we found mainly the analysis of the single rotor [3], since in the Sandia design the rotor was starting near the ground. But this is not enough to obtain accurate results, a good design and a correct estimate of the vibrations impact on the building of the present system configuration. Hence, in this case, it is mandatory to perform a complete analysis of the turbine assembly comprising the rotor and the sustaining pole. The complete analysis would be a loaded analysis in which are considered also:

- the effect of different rotational speeds on the vibration frequencies;
- the effect of aerodynamic forces, at different wind velocities and the interaction between: wind rotor – support pole.

For both cases, the most important is to be evaluated the main forces acting on the structure, and which is the response of the system to different typologies of forces.

The effect of the aerodynamic damping is very important to assess the final fatigue loads. Normally the aerodynamic damping is positive an the main source of damping for the mode shapes, but in particular cases (for example near and in post stall) it could even become negative [4].

Since typically the design solidity of small power VAWTs is quite high, and hence, they work at a lower tip speed ratio than HAWTs, a noise analysis is not compulsory, and consequently it will be omitted from the present study.

3. Forces acting on the rotor

Here the dynamically acting forces which are mostly loading the structure are also briefly introduced.

Dividing them into two main categories [5], these could be:

a) aerodynamic forces: of order ***Np*** (N number of blades), and eventually 1p, if one of the blades is presenting different geometry or pitch angle due to a manufacturing or mounting error.

b) inertial forces: centrifugal forces acting on the blades, which could reflect in static and dynamic unbalancing of the rotor, both of them with a force of order 1p type.

Turbulence is also source for loads with a broadband spectrum. For rotating frames like the wind turbine rotor the turbulence is sampled (so called 'rotational sampling') introducing higher peaks at the order Np.

4. Modal analysis of the VAWT. Simulation and Results

In this article two types of analysis will be presented for the turbine rotor. As mentioned before, the analysis can be performed either only for the rotor structure (blades, rotor shaft), either for the rotor and pole assembly.

First, in this paragraph, the rotor model used for the analysis will be presented. Then the results of the modal analysis for the single rotor are described, investigating the variation of natural frequencies of the structure at different rotational speeds. Finally the modal analysis for the rotor with the support pole is discussed.

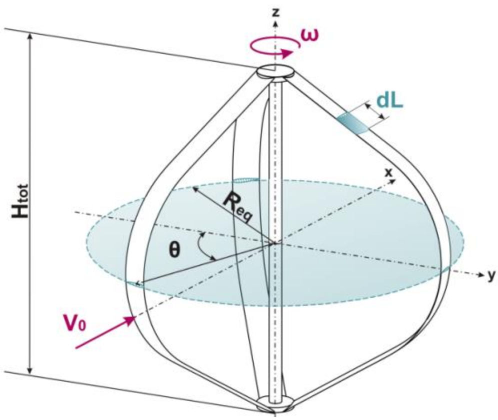


Fig. 1 Vertical axis wind turbine rotor, 3 blades, Darrieus type

4.1. Rotor model

In this paper we studied a small power vertical axis wind turbine that has the following rotor characteristics:

Table 1. Turbine dimensions

H_{tot}	R_{eq}	σ	N	c	Airfoil
[m]	[m]	[-]	[-]	[m]	
2.5	1	0.5	3	0.16	NACA0018

Where: H = height of the turbine, R = maximum radius of the turbine, N = number of blades, c = aerodynamic profile chord length, σ = is the turbine solidity.

This rotor has been designed for an average wind speed of 5 m/s, which is reflecting in a design wind speed of 7 m/s [6]. From previous studies [7] it was proven that the maximum Power Coefficient (CP), for this design, is obtained at a tip speed ratio λ = 2.8, and the design rotational speed is 19.6 rad/s, considering the formula:

$$\lambda = \frac{R\omega}{V_0}$$

The following interest rotational speeds have been defined:

Table 2. Interest rotational speeds of the turbine

rpm	60	120	180	240	300
ω [rad/s]	6.28	12.56	18.85	25.13	31.42

The simulation was performed in Ansys software, considering the geometry of the blades and the materials.

The blades are made of GFRP (glass fibre). It was accepted the convention to use a quasi-isotropic material, in order to facilitate the modelling and the system simulation. Hence, for the turbine was chosen a MAT type material, with small fibres, distributed in more directions.

The material was added to the Ansys library with the properties presented in Table3. Also the rotor shaft is made of composite material. The supporting pole is made of Structural Steel grade S355.

Table 3. Blades composite material properties

Density [kg/m^3]	**Young's Modulus [Pa]**	**Poisson's Ratio**	**Bulk Modulus [Pa]**	**Shear Modulus [Pa]**
1400	7.7e+009	0.3	6.41e+009	2.9e+009

4.2. Modal analysis of the single rotor

The analysis results were used to compute the Campbell diagram, in order to see the critical rotational speeds. The diagram is presented in Fig.2 where:

- for 1p (shaft) and 3p are studied the intersections with the structure natural frequencies, in the range between 6.28 – 31.42 rad/s.
- The critical line for order 1p, corresponding to 1, 2, 3, 4 and 5 Hz, and stays below the natural frequencies values up to 25 rad/s.

- But for order 3p, corresponding to the three blades (with 3, 6, 9, 12, and 18 Hz), the critical rotational speed is at the level of 9rad/s and 28 rad/s.

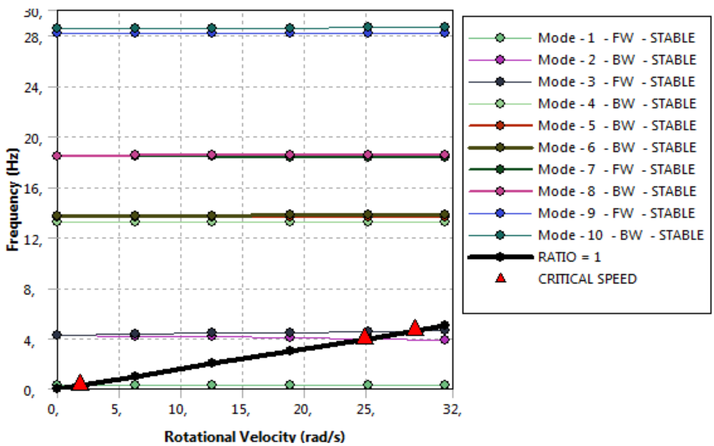
We see that the rotational speed is affecting very little the calculated natural frequencies, so we can conclude that for a typical small VAWT the variation of the natural frequencies is not as critical as for the Sandia design of bigger turbines. This is due generally to higher design solidity for small wind turbines.

4.3. Modal analysis considering the sustaining mast of the wind turbine

For the analysis we considered a 6 m pole, and added also the generator mass as a lumped mass (point mass) of 25 kg.

The pole dimensions are: 6m height, 4mm thickness, 100 mm upper diameter and 130 mm lower diameter. As can be seen in Fig. 6, these dimensions have created a structure with a lower stiffness, which lead to the occurrence of resonance in the structure at rotational velocities of about 8 rad/s and 29 rad/s for the order 1p, and at about 3 rad/s, 10 rad/s, 17 rad/s and 28 rad/s for the order 3p.

Since the design rotational speed of the turbine is 19.6 rad/s, the most critical resonance is the one at 17 rad/s. This is a torsional vibration, and it's due to the coupling of the rotor with the pole torsional mode. With the aim to reduce the effect of this resonance a proper soft control of the generator is essential, in order to decouple the modes. Also the generator control plays an important role to avoid remaining around the critical speeds in start and stop condition [8].



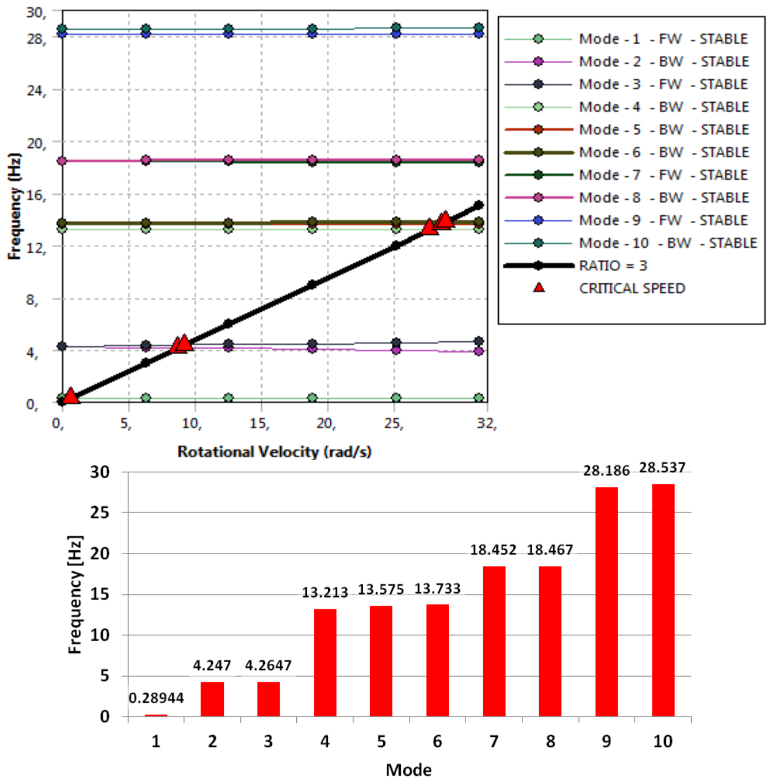
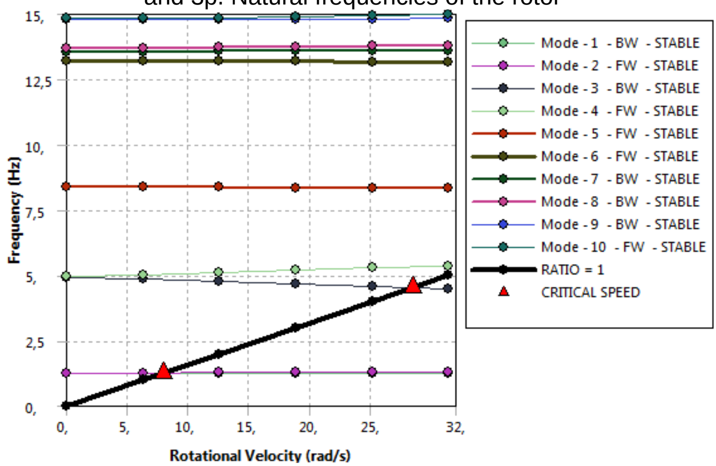


Fig. 2 Campbell diagram with critical rotational speeds for the rotor at 1p and 3p. Natural frequencies of the rotor



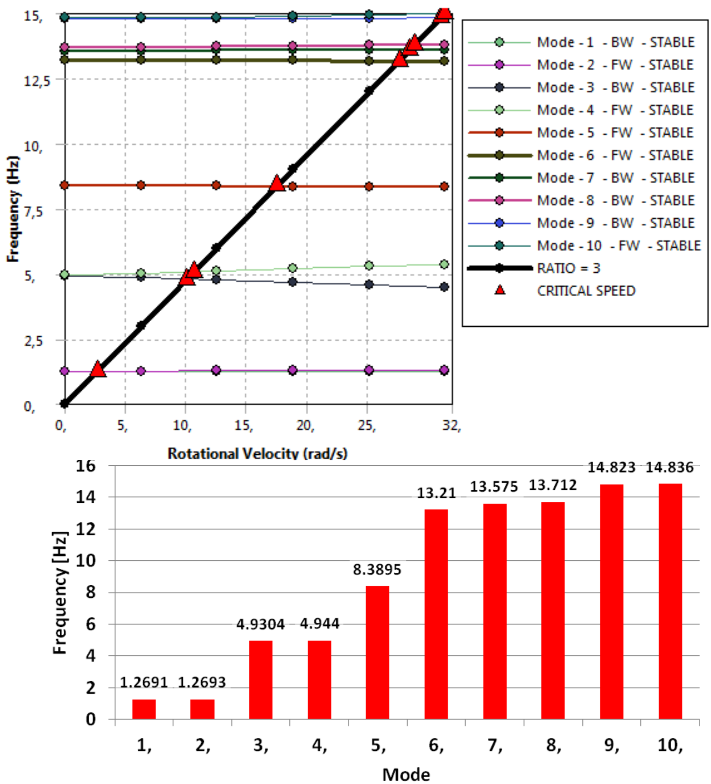


Fig. 3 Campbell diagram with critical rotational speeds for the rotor and pole at 1p and 3p. Natural frequencies of the rotor

5. Conclusions

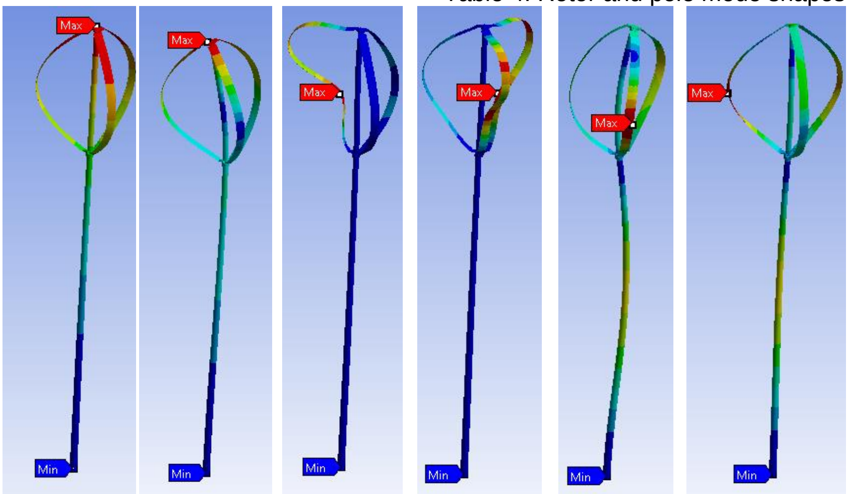
■ The paper presents the main aspects regarding the dynamic structural analysis for a small power vertical axis wind turbine. It emphasized the critical parameters and the types of simulations that need to be performed.

■ As a first step, a modal analysis of the rotor is required. Next the natural frequencies and the critical rotational speeds of the rotor should be studied. For a more accurate modelling, in the third step the aerodynamic forces influence on the natural frequencies should be considered, by coupling results from a CFD simulation together with the modal one.

■ The simplified analysis performed so far in our research, has proven that the correct structural design of the VAWTs is crucial to avoid dangerous resonance situation, as we can see in the Campbell diagram.

Furthermore the rotational velocity is not influencing the natural frequencies for small VAWTs as much as for Sandia design.

Table 4. Rotor and pole mode shapes



Mode 1 - 2 | Mode 3 - 4 | Mode 6 - 7 | Mode 8 | Mode 9 | Mode 10

■ The last analysis takes into consideration also the support pole. This analysis has given also important results: the height and structural design of the pole has a crucial role on the natural frequencies of the whole structure, and a well-designed pole can help increasing the turbine rotational speed variability and increase the turbine safe functioning range.

Moreover the generator control strategy is fundamental to reduce the torsional vibration loads.

■ At higher wind velocities, and higher rotational speeds (i.e. high aerodynamic and inertial loads), such an analysis could give important results regarding the behaviour of the structure, and the impact of the loads on the vibrations from the turbine to the building.

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