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STUDY OF THE SHAPE OF A VERTICAL AXIS MICRO WIND TURBINE WITH WOODEN BLADES

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ABSTRACT

The article illustrates the fluid-dynamic and mechanical analysis of some forms of small-power vertical axis wind turbines, resistant type, whose blades are made of wood and easily workable in a joinery.

In particular, a classical-shaped Savonius, a modified two blades Savonius, a three-bladed Savonius and, again, a rotor with three straight blades having a crescent-moon section, were studied.

A result of the study, worthy of note, concerns the possibility of greatly reducing the mechanical stresses on the support relatively to the rotor having the last shape. This is very important for its installation near inhabited buildings or even integrated into roofs.

Furthermore, the crescent-moon section prototype is able to provide 1 kW power at the nominal wind condition of 12.5 m/s and an annual energy production of 1200-1500 kWh/year, considering a typical urbane site having an average wind speed between 4.5 and 5 m/s.

Keywords: renewable energy, micro wind turbines, wooden blades, CFD simulations, urban integration.

1. INTRODUCTION

Recently developments on small wind turbines for urban areas have gained much attention in a worldwide energy scenario even more affected by the depletion of the fossil fuel-based traditional resources [1]. Among the "green" energies like solar [2], marine [3-4], the wind one is free, clean and renewable. The exploitation of wind resources is spreading, especially in the urban environment, due to the decrease in the number of exploitable sites at convenient costs [5] and to the thrust that smart grids give to power generation near the user [6]. Wind characteristics in urban areas are significantly affected by the roughness of the surface of these areas, fraught of high buildings.

In order to reduce noise levels and to guarantee architectural integration with buildings, vertical axis wind turbines (VAWTs) are preferred, even thanks the absence of wind track devices, such as yaw mechanisms/motors [7].

Drawbacks are usually the pulsating torque produced during each revolution; and the difficulty of mounting vertical axis turbines on tall supports in the city, meaning they must operate in the slower, more turbulent air flow near the ground [8], with lower energy extraction efficiency.

Nevertheless, the suitable shape of the turbine rotor and the use of suitable construction material appears to be crucial in such applications [9]. In wooded areas the diversification and expansion of wood products can contribute to mitigate the critical issue of the short chain, positively affecting the economic value of forests and their management.

Wood is a composite of cellulose and lignin. Wood finds many engineering applications and has long been a common construction material. Furthermore, wood is a natural material and thus environmentally attractive [9]. It is important to note that this use of wood enhances the finest wood species, avoiding their combustion, and stimulates the birth of small local industries in the regions richest in forests, but with low employment rates.

This research aims to study the design criteria of a wind turbine to be made of wood, taking into account the limitations of the material, pulsating torque, performance, urban integration, work and noise. The paper illustrates a fluid dynamic study of four wooden vertical axis wind rotors resistance type, opportunely shaped, i.e. a classical-shaped Savonius, two-bladed modified Savonius, a three-bladed Savonius and, again, a rotor with three straight blades having crescent-moon shaped section. This selection has been made with the aim of obtaining a good starting behavior, ease

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construction and management, as well as the possibility of obtaining a large annual energy production.

For each rotor considered, CFD simulations allowed to define efficiency, starting speed, torque and thrust acting on the support structure, all useful elements for doing an appropriate choice.

2. SHAPE SELECTION CRITERIA

As mentioned in the introduction, this work analyzes some prototype solutions, taking into account two constraints. Clearly, the first and most important limitation concerns the possibility of wood construction. The particular shapes, such as helical impellers, which would require particularly laborious construction technologies do not adapt to the present idea and have not been taken into consideration.

A second constraint regards the efficiency, which must not be below a certain threshold. This threshold is evaluated with reference to a turbine of equal power, present on the market and which has the best performance characteristics, built with the most advanced materials.

The maximum power coefficient for this reference turbine, having power around 1 kW, is estimated at around 30% [10].

Therefore, a value not less than 15% has been assumed as the lower limit.

The prototypes that have satisfied the two constraints have been extensively analyzed: the characteristic curve has been reconstructed, the optimal operating point calculated, the solidity, the weight, the starting torque, the thrust, the stresses and the structural resistance.

3. CFD METHODOLOGY

The simulations were carried out is ANSYS Fluent 19.2 environment [11], by using an approach two-dimensional and not stationary. The diameter of the turbines under test is 1m.

The domain, see fig. 1, has been subdivided into two sub-domains, a circular one that contains the turbine and rotates together with it, and the other rectangular stationary, which communicate with the first through the so-called "contact region". The rotating domain, due to its complexity, was reconstructed with triangular cells having a unit growth ratio, with the exception of the layer near the wall, that required a quadrangular grid structure. The stationary rectangular domain was reconstructed with quadrilateral cells and, near the interface, with a structured grid having a reduced and variable growth factor from 1.05 to 1.2.

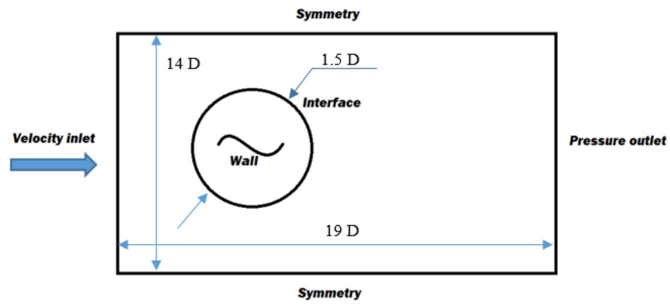


Fig 1 Computational domain and boundary conditions

The independence of the solution from the mesh was certified by discretizing the domain with various grids, characterized by a growing degree of refinement, accepting a maximum error of 3% compared to the finest mesh that was reconstructed with 708,000 elements.

The turbulence has been solved by applying the k-ω SST model, which by default incorporates the most advanced wall treatment (LRN - Low Reynolds Number), with resolution of the viscous substrate and which requires a more refined wall treatment ($y^+ < 1$). This model, characterized by greater accuracy, required high computational resources but proved to be indispensable for conclusive tests and in the characterization of particularly delicate performance indices.

The solver used is the "pressure based", while for calculating the pressure-speed equations, the SIMPLEC algorithm (Semi- Implicit Method for Pressure Linked Equations - Consistent) was adopted. The interpolation scheme of the pressure is the PRESTO scheme! (PREssure STaggerring Option), as it is suitable for rotating flows and with high curvatures. To calculate the flow in the transition between the stationary and the rotating domain, and vice versa, an interface grid has been created. The condition of imposition of the rotor mesh was imposed through the "moving mesh" command which assumes the "sliding mesh" model. On the turbine blades, on the other hand, no-slip conditions have been set along with the condition of relative movement of zero moving wall with respect to the adjacent area. As a general criterion, a time discretization was performed, requiring that in the assigned time step allows the rotor to revolve only 1° [12]. The convergence criteria used provided that the average torque coefficient would not exceed a deviation of 1%, compared to the values of the previous period, corresponding to a rotation of 360°, while for the residuals, for each time step, was set equal a 10^{-5}.

The various simulations were carried out by imposing a constant rotation speed on the rotating domain (wind turbine). The values used in the various tests are included in the following range: 0.1-40 rad/sec.

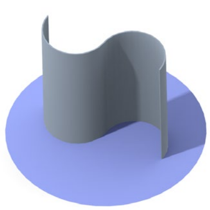
The performance parameters were calculated with the following speeds of the undisturbed current:

- characteristic curve calculated at 7 m/s;
- torque at 2.5 m/s and rotor stopped (to have information about starting torque) ;
- stresses at 20 m/s (maximum operating speed)
- thrust at 30 m/s with machine stopped (to have information about the overturning moment).

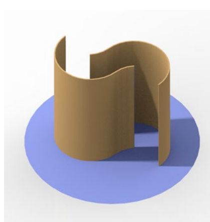
The proposed k-ω SST turbulence model was validated on the basis of the experimental tests carried out at the Sandia laboratories in New Mexico [13].

4. PROTOTYPES TYPOLOGY

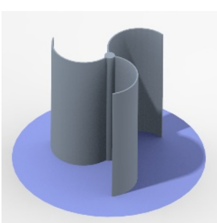
The chosen turbine is of the resistance type, for easy starting even with low speed winds.



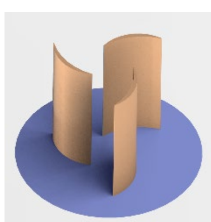
***a)** Classic Savonius*



***b)** Modified Savonius*



***c)** Three-bladed Savonius*



***d)** "Crescent moon" blades*

Fig 2 Prototypes of wooden wind turbines.

The following prototypes were considered (Fig. 2):

• *Classic Savonius* turbine, with a conventional S shape;

• *Modified Savonius* turbine modified with an increase in the size of the half-cylinders, which thus overlap for almost half of their diameter and for an angle of 25 °, in a plane system of polar coordinates, having the origin coinciding with the vertical axis of the rotor;

• *Three-bladed Savonius* turbine, consisting of three semi-cylinders;

• "*Crescent moon*" turbine with three blades having a "crescent moon" shaped section. This kind of blade has a smaller width and it can be anchored with spokes to the shaft, making the machine more streamlined.

The last configuration (fig. 2d), has been derived from the classical three-bladed Savonius (fig. 2c).

5. RESULTS

Before presenting the results, it is necessary to specify that numerical simulations alone are not a comprehensive research tool. It is necessary that they be accompanied by a critical spirit in the analysis of the results obtained, especially when it is essential to reduce the number of simulations. All the results herein shown refer to an area swept by turbines of (1x1) m^2.

Among the turbines in question, the classic Savonius rotor (fig. 2a) expresses a good efficiency, even with relatively high peripheral speed ratio coefficients. This behaviour can be explained by observing fig. 3, which represents the velocity vectors: the curvature of the profile creates a relative narrowing of the streamlines and therefore an acceleration of the flow with the generation of an additional lift force [14].

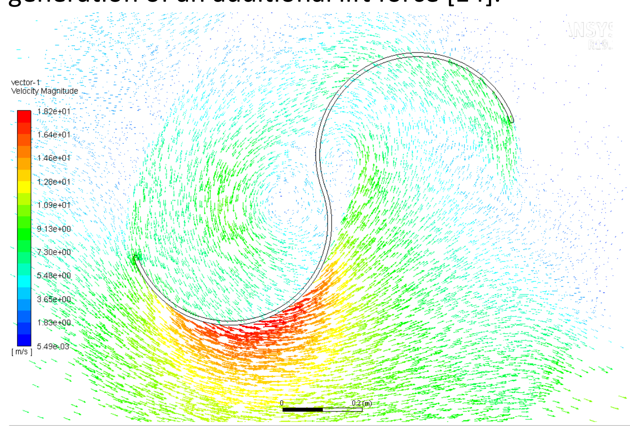


Fig 3 Velocity magnitudo contours - Classic Savounius

Despite the high efficiency of the turbine, due to the low starting torque, there are some difficulties when starting up. Furthermore, due to the irregularity of the torque and the high-pressure fields, the structure is subject to significant stresses.

CFD simulations have confirmed that increasing the number of blades leads to a decline in the efficiency of the machine, but less fluctuations in the torque delivered, resulting in lower stresses, both static and fatigue. By adding another blade, the material used increases (see figure 2c). With the aim of reducing it, without changing the external diameter, a new configuration, with shorter blades in radial extension and aerodynamic shape, was obtained by removing the connection between the inner end of the profiles and the turbine axis. In this case, since the blades are detached from the axis, the use of spokes becomes necessary. As a result, the "crescent moon" configuration of fig. 2d is reached, in which the profile has a shorter chord and a variable thickness. By reducing the extension of the blade profiles, the bending stresses induced by the wind on them decrease and the wooden construction is simplified. Furthermore, this configuration has the additional advantage of a more regular torque, with contained oscillations.

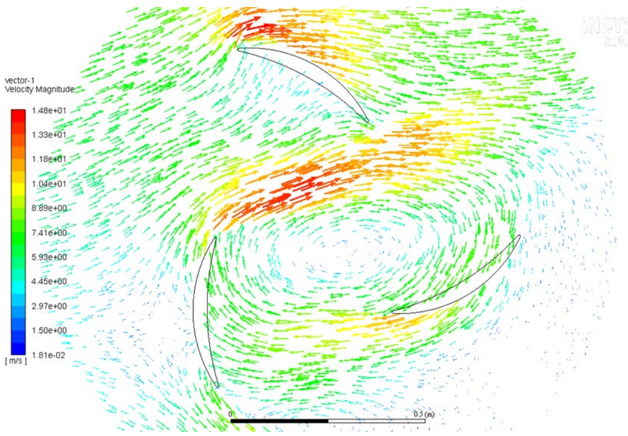


Fig 4 Velocity magnitudo contours "crescent moon" blades 1^ configuration

Fig. 4 depicts the velocity magnitudo contours of a first "crescent moon" configuration characterized by a short chord: the wind flow, coming from the left, impacts on the lower profile thus increasing its speed (central red zone), but it is not intercepted by the blade immediately downstream. This affects the performance of the prototype, which will not be optimal. For this reason the design has been modified by increasing the chord of the blades profile. In such a way, the velocity magnitudo contours of fig. 5 demonstrate a better behaviour and consequent better efficiency. In any case, its efficiency is not the highest, but it is intermediate between those shown by the classic Savonius rotors with two and three blades.

Table 1 shows the main characteristics of all the examined turbines, i. e. the power coefficient *Cp*, the tip speed ratio λ, the starting torque, the torques and the forces oscillations at nominal wind speed, the angular variation of the forces direction, the thrust (so the overturning moment), the blade solidity, the visual and the acoustic impact.

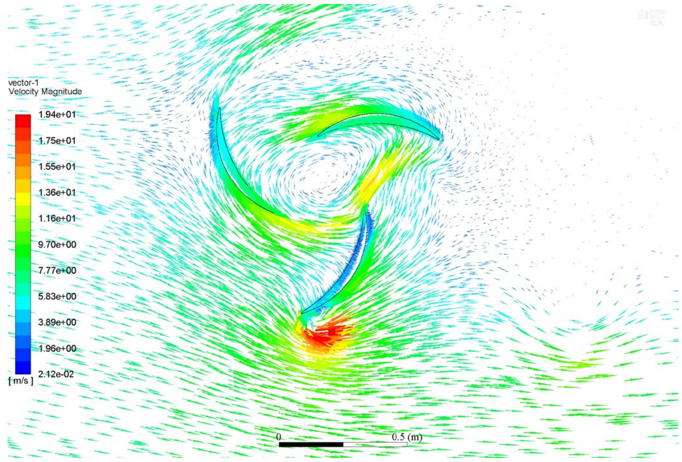


Fig 5 Velocity magnitudo contours "crescent moon" blades 2^ configuration

Table 1 Characteristic operating parameters of the prototypes

		Classical Savonius (fig. 2a)	Modified Savonius (fig. 2b)	3 Blades Savonius (fig. 2c)	Crescent-moon (fig. 2d)
C_{PMAX}		0.225	0.230	0.165	0.180
λ_{OPT}		0.8	0.85	0.8	0.5 / 0.6
Starting torque [Nm]		0.4	0.62	0.36	0.63
torques oscillations	MAX [Nm]	11.2	10	5	7.8
	Amplitude	11.2	8.8	3.4	5.8
Forces oscillations	MAX [N]	600	500	500	430
	Amplitude	400	300	220	130
Force angular variation [°]		60°	45°	40°	23°
Thrust [N]		1720	700	800	680
Blade solidity		1.57	2.26	2.14	1.35
Use of spokes		No	No	No	Yes
Visual impact		MID	MID	MID	LOW
Acoustic impact		LOW	LOW	LOW	LOW

Table 1 substantially summarizes the sequence of analyses carried out in the search for an optimal shape, under various technical aspects, passing from the classical 2-bladed Savonius (second column of table 1) to the 3-bladed configuration with a crescent moon shape (fifth column of table 1). The worst performances expressed by the turbines are highlighted in orange, while the best ones are highlighted in green.

The modified Savonius (fig. 2b – third column of table 1) is the first step of the prototype investigation respect to the classical 2-bladed Savonius. Compared to this latter it has recorded better fluid-dynamic performance and lower stresses, above all with regard to the thrust passing from 1720 N to 700 N, this value implies a predisposition to a heightening of the turbine, reducing its bulkiness on the ground.

Regarding the starting torque, the improvement is tangible; the average torque value on a complete revolution is 0.62 Nm for the modified Savonius, against a torque of 0.40 Nm for the classic Savonius, and furthermore there are no positions, with respect to the wind direction, in which this exhibits critical points of negative torque.

The configuration of the three-bladed Savonius (fourth column of table 1 - fig. 2c), despite having a power coefficient value of about 30% lower with respect to the classical Savonius (Cp=0.165 vs Cp=0.225), exhibits a greater regularity of torque (maximum value 5 Nm and maximum oscillation of 3.4 Nm – see fourth column of table 1) and therefore lower stresses. For this reason, the authors tried to improve the three-blade configuration by adopting variable-section profiles and designing the *crescent moon* configuration whose characteristics are highlighted in the fifth column of table 1.

The *crescent-moon* turbine exhibits good behaviour with respect to almost all the parameters (see table 1 - green cells) with the exception of the power coefficient, which is slightly higher only compared to the classic three-blade configuration (see fourth column). Moreover, a preliminary structural analysis of the finite elements (FEM) was carried out, by loading the blades with a constant pressure of 1000 Pa and a centrifugal force deriving from a rotation of 20 rad/s. With regard to the stress state, values of almost 3 Mpa are found for almost the entire surface, which are abundantly below the limit of resistance of the material and demonstrate the full compatibility of the wood for the construction of the blades.

Figure 5 shows the power coefficient (C_P) curves as a function of the tip speed ratio (λ) for the three turbines. The crescent moon turbine, despite being far from the efficiency of the classic Savonius, for low λ values shows relatively high C_P values, which implies a better management of the transients from start-up to the nominal speed. Moreover, it reaches the maximum power coefficient (Cp = 0.165) for a tip speed ratio λ = 0.5, which is lower than the other configurations (both have λ = 0.8), thus implying slower rotations and consequent reduced noise. Figure 6 illustrates the variations of the starting torque by changing the wind direction angle. The trend seems good, with an average value on the overall range, of 0.63 Nm. The curve, for range of rotation of about 80° (from 40° to 120°) is almost flat, with values higher than 0.8 Nm and a drop in a narrow range of 20 °, which brings it up to a minimum value of 0.1 Nm. The minimum peak extends for a limited angle excursion, while the average value is mostly the highest, so there are no problems at startup.

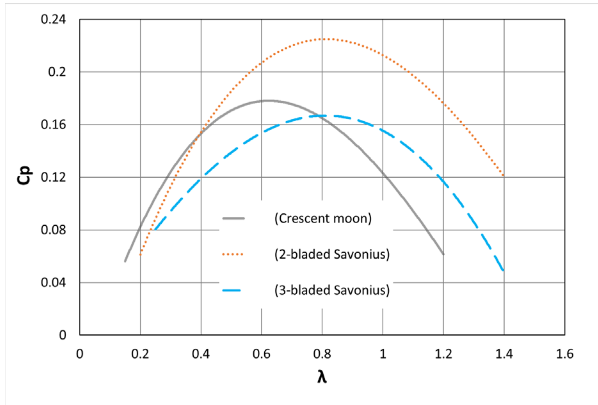


Fig 5 C_P curves as function of λ

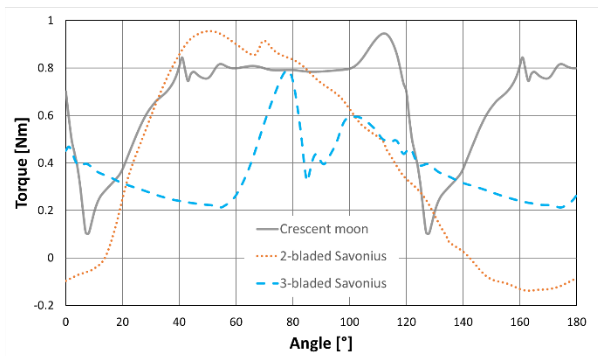


Fig 6 Starting torque a 2.5 m/s

Downstream of this comparison, next step is the construction of a prototype crescent-moon type that uses two modules assembled on the same axis and mounted with a 60 ° phase shift, with a diameter of 2m and a height of 1.5 each. In this way, the nominal power, with a wind speed of 12.5 m / s, is 1 kW, while the annual energy yield would be around 1200-1500 kWh.

6. CONCLUSIONS

The present work concerned the study of the shape to be assigned to a vertical axis wind turbine to allow its easy making in woody material, more suitable for integration in an urban context. This machine will be able to reach a satisfactory effectiveness, even if it has to exploit a weaker and more turbulent wind. The turbine is of the resistance type, to favour the starting capacity, even with low speed winds, and to obtain an appreciable annual energy production. The forces acting on the blades, the drive torque and the power generated were calculated through CFD analysis.

Initially, three main resistance rotors have been tested, all of which can be classified as Savonius wind turbines: the classic 2-blade rotor, one with 2 modified blades and the 3-blade Savonius.

It was understood that by augmenting the blade number from 2 to 3 the stresses diminish, the torque become more regular with contained oscillations but the efficiency decreases because if a blade is in optimal incidence conditions, extracting the maximum energy from the flow, the others blades are disturbed from the flow itself which interferes their path.

For this reason, subsequently, a new prototype with 3 blades having a "crescent moon" shaped section has been analysed and studied.

This rotor has good qualities with respect to starting torque, uniformity of the torque delivered, stresses and vibrations transmitted to the structure and operates at a lower rotation speed. However, the power coefficient is not the highest. Given the importance of this parameter, future developments will be conducted in order to improve it, perfecting the shape of the rotor. Verifications were carried out on the rotor structural behaviour, under static conditions through FEM analysis, introducing the substantial approximation to consider the wood (lamellar, what is expected to be used) as an isotropic material. The verification was largely satisfactory therefore it is possible to consider the results obtained as reliable, despite the approximations introduced.

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