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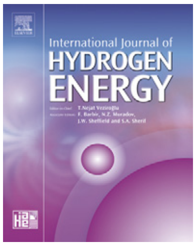

Computational method for the design of wind turbine blades

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ABSTRACT

Zeus Diseñador was developed to design low-power, horizontal-axis wind turbine blades, by means of an iterative algorithm. With this software, it is possible to obtain the optimum blade shape for a wind turbine to satisfy energy requirements of an electric system with optimum rotor efficiency. The number of blades, the airfoil curves and the average wind velocity can be specified by the user. The user can also request particular edge conditions for the width of the blades and for the pitch angle. Results are provided in different windows. Two- and three-dimensional graphics show the aspect of the resultant blade. Numerical results are displayed for blade length, blade surface, pitch angle variation along the blade span, rotor angular speed, rotor efficiency and rotor output power. Software verifications were made by comparing rotor power and rotor efficiency for different designs. Results were similar to those provided by commercial wind generator manufacturers.

1. Introduction

The main problem of a wind turbine generator design project is the design of the proper helix, to satisfy the specific energy requirement of an electric system with optimum performance.

Wind turbine rotor performance is usually characterized by its power coefficient [1,2]:

$$\eta = \frac{\text{Rotor power}}{\text{Power in the wind}} = \frac{P}{\rho A v^3/2} \qquad (1)$$

where ρ is the air density, v is the average wind speed and A is the rotor area (area of the rotor disc). Since P is a function of rotor angular speed Ω, and also depends on the airfoil, the shape and the layout of the blades, it is necessary to use iteration to calculate rotor efficiency η [2,3].

2. Aerodynamics of horizontal-axis wind turbines

2.1. Blade element theory

Consider a turbine with N blades of tip radius R each with chord c and set pitch angle β. Both the chord length and the pitch angle may vary along the blade span. Let the blades be rotating at angular velocity Ω and let the wind speed be U_∞. For an annular section of radius r and thickness dr inside the rotor area, the tangential velocity Ωr of the blade element combined with the tangential velocity of the wake $a'_r\Omega r$ means

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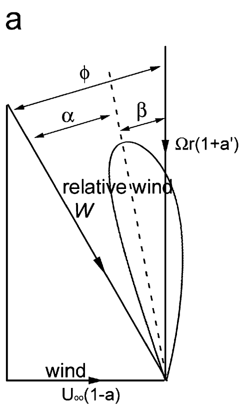


Fig. 1 – Blade element velocities (a) and forces (b).

that the net tangential flow velocity experienced by the blade element is $u = (1 + a_r')\Omega r$ [2,3]. Thus, the resultant relative velocity W on the blade is (see Fig. 1)

$$W = \sqrt{U_\infty^2(1-a_r)^2 + (\Omega r)^2(1+a_r')^2} \qquad (2)$$

which acts at an angle ϕ to the plane of rotation, such that

$$\sin\phi = \frac{U_\infty}{W}(1-a_r) \qquad (3)$$

$$\cos\phi = \frac{\Omega r}{W}(1+a_r') \qquad (4)$$

a_r and a_r' are the axial and angular inductor factors for a radius r [2–4].

The angle of attack α is the angle between the chord line and the relative wind W, and it is given by $\alpha = \phi - \beta$.

Airflow over an airfoil produces a distribution of forces over the airfoil surface. The resultant of these forces is usually resolved into two forces: the lift force L, defined to be perpendicular to the direction of W, and the drag force D, defined to be parallel to the direction of W.

The forces of the blades of a wind turbine can be expressed as a function of lift and drag coefficients C_D and C_L, obtained from the airfoil characteristic curves $C_D(\alpha)$ and $C_L(\alpha)$, at a certain value for α [2,5]:

$$D = 0.5\rho W^2 N c C_D \qquad (5)$$

$$L = 0.5\rho W^2 N c C_L \qquad (6)$$

2.2. *Determination of rotor torque and power. The blade element momentum theory*

The element of axial rotor torque caused by aerodynamic forces on N blade elements of chord c is [2,5]

$$dq_r = 0.5\rho W^2 N c(C_L \sin\phi - C_D \cos\phi) r\,dr \qquad (7)$$

The complete rotor, therefore, develops a total torque Q:

$$Q = \int_{R_i}^{R} q_r\,dr \qquad (8)$$

The actual rotor area is

$$A_D = \pi(R^2 - R_i^2) \qquad (9)$$

where R and R_i are the tip and the internal radiuses of the helix, respectively.

The change of angular momentum of the air passing through the rotor disc is [5]

$$Q = \pi(R^4 - R_i^4)(1-a_r)a_r' U_\infty \Omega \qquad (10)$$

Equating the two moments for the rotor torque (Eqs. (8) and (10)):

$$a_r'(1-a_r) = Q^* = \frac{NcW^2}{8\pi\Omega r^2 U_\infty}(C_L \sin\phi - C_D \cos\phi) \qquad (11)$$

The power developed by the rotor is

$$P = Q\Omega \qquad (12)$$

It can be seen from Eqs. (10) and (12) that the calculation of torque and power developed by the rotor requires the knowledge of the flow induction factors a_r and a_r', which are obtained by solving Eq. (11). The solution is carried out iteratively, because of the non-linearity of the airfoil characteristics with the angle of attack.

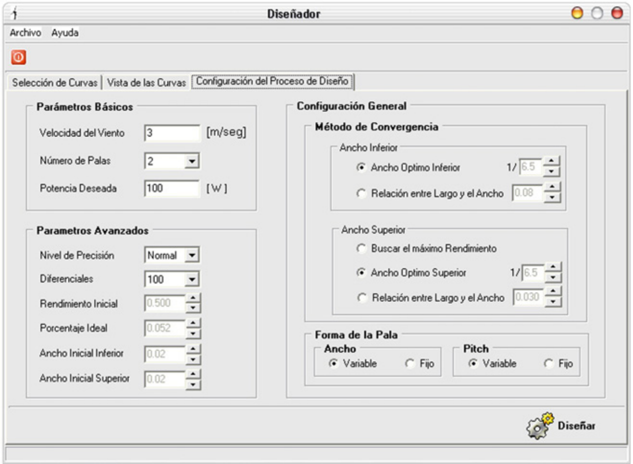
3. Rotor design procedure [5]

The software allows the user to input the desired values for rotor efficiency ("*Rendimiento Inicial*" in Fig. 2), wind speed ("*Velocidad del Viento*" in Fig. 2), number of blades ("*Cantidad de Palas*" in Fig. 2), rotor power ("*Potencia Deseada*" in Fig. 2) and the ratio x (named "*Porcentaje Ideal*" in Fig. 2) between the internal radius R_i and the tip radius R (designated "*length*", "*Largo*" in the software). With these values:

1. The program calculates an initial tip radius:

$$Length = \sqrt{\frac{RotorPower}{[\frac{1}{2}\rho(WindSpeed)^3\pi(1-x^2)] \times RotorEfficiency}} \qquad (13)$$

2. With this calculated value and with the information of the airfoil curves chosen by the user, the software obtains the value of P (see Eq. (12)) by solving Eq. (11), and it calculates the actual efficiency (named *Rendimiento Real* in the



Parámetros Básicos
Velocidad del Viento 3 [m/seg]
Número de Palas 2
Potencia Deseada 100 [W]

Parametros Avanzados
Nivel de Precisión Normal
Diferenciales 100
Rendimiento Inicial 0.500
Porcentaje Ideal 0.052
Ancho Inicial Inferior 0.02
Ancho Inicial Superior 0.02

Configuración General
Método de Convergencia
Ancho Inferior
● Ancho Optimo Inferior 1/ 6.5
○ Relación entre Largo y el Ancho 0.08
Ancho Superior
○ Buscar el máximo Rendimiento
● Ancho Optimo Superior 1/ 6.5
○ Relación entre Largo y el Ancho 0.030
Forma de la Pala
Ancho ● Variable ○ Fijo
Pitch ● Variable ○ Fijo

Fig. 2 – Configuration window.

following equations):

$$ActualEfficiency = \frac{P}{\frac{1}{2}\rho(WindSpeed)^3\pi(1-x^2)Length} \qquad (14)$$

3. Using this calculated efficiency, the program calculates a new value for the tip radius with Eq. (13) as follows:

$$Length = \sqrt{\frac{RotorPower}{[\frac{1}{2}\rho(WindSpeed)^3\pi(1-x^2)] \times ActualEfficiency}} \qquad (15)$$

4. The process continues from step 2 until no significant improvement is observed in the calculated efficiency value of Eq. (14).

4. General aspects of the visual interface of the software [6]

The visual interface has three windows. The first one is destined for the selection of the airfoil characteristics curves C_D and C_L. The second one displays the selected profile and the corresponding curves. In the last one, the user can configure the design as follows.

4.1. *Design configuration window*

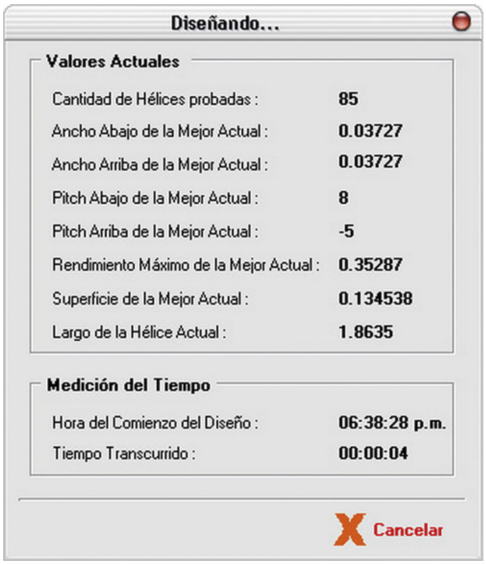
This window has four principal sectors (see Fig. 2): "*Parámetros Básicos*" (basic parameters), "*Párametros Avanzados*" (advanced parameters), "*Método de Convergencia*" (covergence criterion) and "*Forma de la Pala*" (blade shape).

The "*Parámetros Básicos*" sector is destined for the input of wind speed ("*Velocidad del Viento*"), number of blades ("*Cantidad de Palas*") and rotor power ("*Potencia Deseada*").

The advanced parameters (in "*Parámetros Avanzados*" sector) are the values used by the program for the iterative process. They are predetermined, but they can be changed by the user. These parameters are precision level ("*Nivel de Precisión*" in Fig. 2), number of differential elements ("*Diferenciales*" in Fig. 2), initial efficiency value ("*Rendimiento Inicial*" in Fig. 2), ratio x ("*Porcentaje Ideal*" in Fig. 2) between the internal radius R_i and the tip radius R, and initial values for the ratios between the length and the width of the blade at the tip radius ("*Ancho Inicial Superior*" in Fig. 2) and at the internal radius ("*Ancho Inicial Inferior*" in Fig. 2) of the helix.

The user can choose between two convergence criteria (in "*Método de Convergencia*" sector): (1) By selecting the option "*Ancho Óptimo Inferior*" and "*Ancho Óptimo Superior*", the algorithm stops when the improvement percentage of the calculated efficiency value with respect to the increase of the blade surface exceeds a value specified by the user (6.5 in Fig. 2); this value depends on the profile of the blade and on the Reynolds number. (2) By selecting the option "*Buscar el Máximo Rendimiento*", the algorithm stops when it is no longer possible to increase the calculated efficiency value for defined ratios between the width and the length of the blade at the tip radius and at the internal radius of the helix.

The user can define whether he wants a variable width along the blade span or not ("*Forma de la Pala*" sector). He can also choose between a constant and a variable pitch angle.



Cantidad de Hélices probadas : 85
Ancho Abajo de la Mejor Actual : 0.03727
Ancho Arriba de la Mejor Actual : 0.03727
Pitch Abajo de la Mejor Actual : 8
Pitch Arriba de la Mejor Actual : -5
Rendimiento Máximo de la Mejor Actual : 0.35287
Superficie de la Mejor Actual : 0.134538
Largo de la Hélice Actual : 1.8635

Hora del Comienzo del Diseño : 06:38:28 p.m.
Tiempo Transcurrido : 00:00:04

Fig. 3 – Design process window.

4.2. *Design process display*

It is possible to see how the design process is working (see Fig. 3). The design process can also be aborted with the cancel button ("*Cancelar*" in Fig. 3).

5. Results display [6]

Results are provided in different windows (Figs. 4 and 5). Numerical results are displayed for blade length, blade surface, pitch angle variation along the blade span, rotor angular speed, rotor efficiency and rotor output power (Fig. 4). Two- and three-dimensional graphics show the aspect of the resultant blade (Figs. 4 and 5).

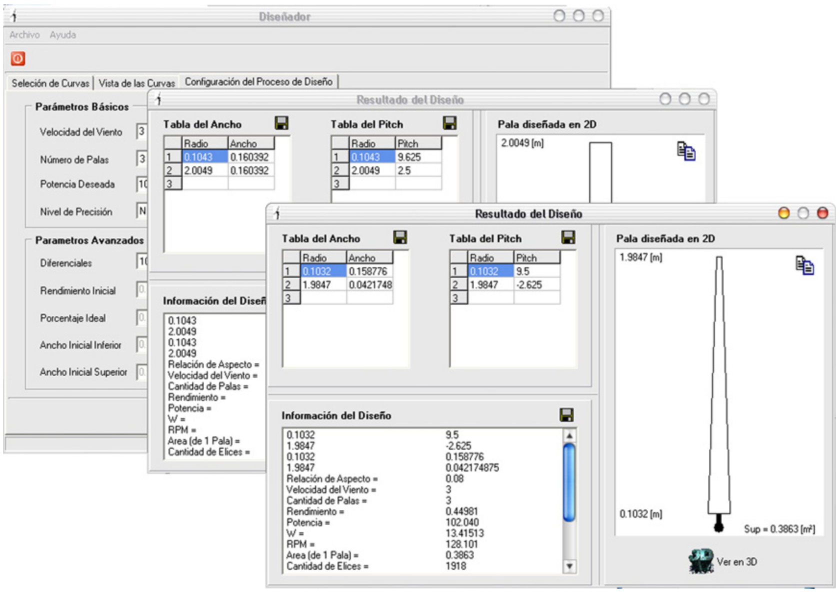
The software allows the accumulation of different design result windows (Fig. 4), in order to compare performance values and blade shapes.

6. Practical designs and discussion

Rotor shapes are usually not optimum because of fabrication difficulties. Furthermore, when an optimum blade is run at a different angular velocity than the one for which it was designed, it is no longer "optimum". Thus, blade shapes must be designed for easy fabrication and for overall performance over the range of wind and rotor speeds that they will encounter. Considering this, a comparative approach must be used, as in the following example.

A turbine with two blades was designed to generate 100 W with an average wind of 3 m/s. The ratio of the internal to the tip radiuses was set at 5.2%.

For an easy and cheap construction, constant width along the blade span was selected, and the Naca 2412 airfoil was chosen with a Reynolds number of 60,000. The software results were: 0.34103 rotor efficiency, 102.042 watts rotor power, 0.6605 square meters for each blade.



Resultado del Diseño

Tabla del Ancho

	Radio	Ancho
1	0.1043	0.160392
2	2.0049	0.160392
3		

Tabla del Pitch

	Radio	Pitch
1	0.1043	9.625
2	2.0049	2.5
3		

Resultado del Diseño

Tabla del Ancho

	Radio	Ancho
1	0.1032	0.158776
2	1.9847	0.0421748
3		

Tabla del Pitch

	Radio	Pitch
1	0.1032	9.5
2	1.9847	-2.625
3		

Información del Diseño

0.1032	9.5
1.9847	-2.625
0.1032	0.158776
1.9847	0.042174875
Relación de Aspecto =	0.08
Velocidad del Viento =	3
Cantidad de Palas =	3
Rendimiento =	0.44981
Potencia =	102.040
W =	13.41513
RPM =	128.101
Area (de 1 Pala) =	0.3863
Cantidad de Elices =	1918

Fig. 4 – Accumulated windows. 2D graphics.

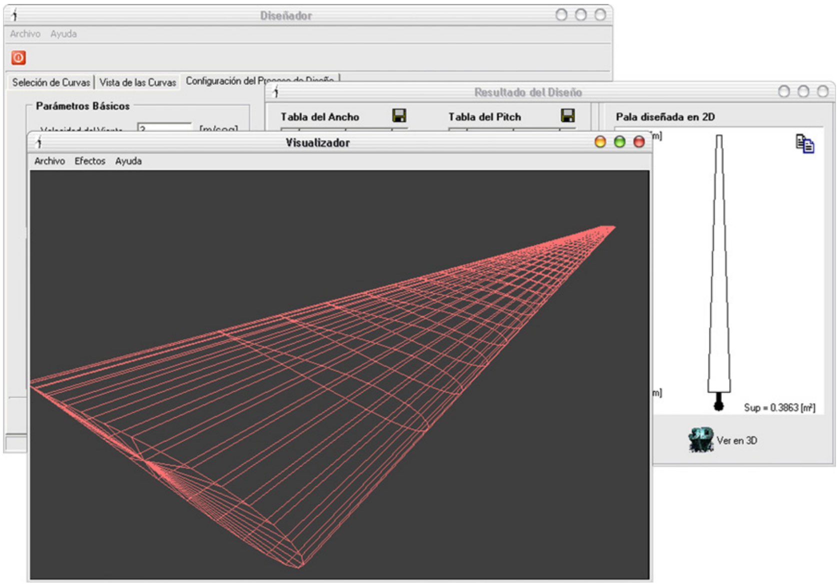


Fig. 5 – 3D graphic.

For a smoother surface, a Reynolds number of 250,000 was chosen. The results were: 0.42564 rotor efficiency, 102.045 W rotor power, 0.5645 m^2 for each blade (less weight than the previously designed blades and better performance).

For variable width along the blade span (but same profile and same Reynolds number), the results were 0.44394 rotor efficiency, 102.035 W rotor power, 0.4832 m^2 for each blade. It can be seen that these blades have a better performance and are smaller (and therefore lighter), but they are more expensive because of the difficulty of construction, due to their smooth surface and variable width.

A more sophisticated profile (which requires precise manufacture) is the Naca 6312 with a Reynolds number of 250,000. The results of the program design were 0.45645 rotor efficiency, 102.035 W rotor power, and 0.4597 m^2 for each blade.

7. Conclusions

With this program, it is possible to develop very different designs for many different situations, in order to devise cheap or expensive projects, and simple or sophisticated precise constructions.

The software tests were made comparing rotor power and rotor efficiency for different designs. Results were similar to those provided by commercial wind generator manufacturers.

Acknowledgements

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