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## Development of Vertical Wind Turbines via FDM Prototypes

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### Abstract

In the present work, we propose to design and manufacture a specific Vertical Axis Wind Turbine (VAWT) prototype in order to evaluate its performance when some geometrical parameters are modified. The key idea is to take advantage of additive manufacturing flexibility to print the main components in an easy way and at low cost. Prototype size (scale 1:250, with respect to a 2 MW wind turbine) is small enough to be tested in a 40 cm x 40 cm wind tunnel. We use a Fused Deposition Modeling (FDM) machine to print the prototype, which is previously designed via CAD software. Different tests have been performed to determine an adequate printing configuration, mainly regarding how layer height influences roughness and printing time. Main dimensions, roughness and weight of the printed pieces were measured and finally, parts of highest quality were used to assemble a working prototype. The methodology presented in this paper shows it is possible to manufacture a wind turbine prototype with the following characteristics: flexibility to modify the design throughout the course of the investigation, low cost and low time needed to obtain the components with enough quality.

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### 1. Introduction

In the recent years, the offshore wind energy has been developed worldwide. This kind of renewable energy is being supported by European governments fundings, e.g. through the H2020 framework programme for research and innovation, counting with numerous examples of projects in Germany, France and Great Britain [1], whose aim is to decrease the European Community's energy dependency, although this goal is still far from being achieved [2].

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On the other hand, the offshore wind energy can be divided into two categories, based on the type of windmill, namely, bottom-founded windmills and floating windmills. The latter type is rising the interest of those countries whose coasts are deep, as demonstrate the large amount of research proposal being investigated in Japan, Italy, USA, Norway, Spain and Portugal, among others [3].

The floating offshore wind energy is still under development, and the performance of windmill prototypes are still being investigated in test facilities. Some of those full-scale facilities consist of arrays of floating horizontal axis wind turbines (HAWT). However, HAWTs are mainly optimized for onshore applications, what creates some structural and performance problems along with a high cost [4].

Considering those difficulties, the development of vertical axis wind turbines (VAWT) constitutes an interesting approach, since its kinematics and dynamics might be advantageous with regard to the structural design of the offshore assembly. In this sense, VAWTs are historically less developed than HAWTs [5], what encourages us to manufacture and test a VAWT prototype (Darrieus's type) in order to evaluate its suitability for offshore applications.

In the present work, we propose to design and manufacture a particular VAWT model. This prototype will be used to evaluate its performance when some geometrical parameter are modified, which avoid performing time-consuming and computational demanding three-dimensional numerical simulations of the flow around the turbine. This experimental approach might represent a more realistic option to test the performance of different VAWT geometries in an easy and low-cost way. The methodology proposed is intended to open the research field in wind turbines, because we will show that expensive equipment are not needed.

From the point of view of design, and in line with the idea exposed above, we have developed a transformable prototype model, with the aim at testing a large number of geometrical configurations, being it possible to evaluate advantages and inconveniences of several versions.

Regarding the manufacturing process, the methodology employed constitutes a novel way when compared with other research prototypes, since the use of a 3D printer allows to reduce the size. The latter translates into a lower material investment and shorter manufacturing time, with respect to aluminum, carbon fiber or wood models [6]. Thus, the present work demonstrates that rapid prototyping tools allow the manufacturing of models with a more affordable and reasonable budget.

### Prototype design

The key idea is to develop and manufacture a flexible and cheap Darrieus turbine mock-up, which might help to test different geometrical wind turbine configurations. Regarding its flexibility to perform meaningful experiments, we have based our design on the main parameters studied in recent research works for VAWT [7]. We summarize below the main parameters taken into account in our study:

- Diameter
- Number of Blades
- Type of Blades (NACA series)
- Chord of Blades
- Azimuthal variation of pitch blade angle [8]

### Design constraints

The mock-up design has been performed considering the following constraints:



Fig. 1. Wind tunnel

- The model must be a Darrieus-type wind turbine, which has been selected due to its suitability for Floating Offshore Wind Farms.
- Printed components size is limited to 200x200x150 mm, in the X, Y and Z directions respectively, which corresponds to the working zone of the BCN3D Printer.
- Mock-up final size included within the limits 400x400 mm (Y, Z axes); which correspond to the wind tunnel testing section that will be employed in future research with the actual prototype. View Fig. 1.
- Pre-installed prototype size contains within a vertical cylinder of 200 mm diameter; to allow access to the wind tunnel testing area.
- Use of standardized components, e.g. screws, nuts, bearings, etc; as an overall design rule, since it translates into a lower manufacturing cost.
- To minimize the overall budget through an appropriate model design.

### Design tools

The prototype has been designed using a CAD software, and more precisely, Catia Version V5 (R19). The reasons for this choice are [9]:

- A powerful parametric design, which allows the automatic modification of the dimensions characterizing the model. This feature will translate into a considerable time reduction if the parameters are updated based on the research results obtained with the first prototype.
- A good working accuracy, given by a wide working interval (from 1 m to 100 km), and a narrow precision of fit, between 0.01 micron and 0.1 mm. (Table 1.)
- The kinematics toolbox performs mechanisms simulations, allowing a deep analysis of movements and numerical results, such forces, velocities and accelerations.
- Great capability to define complex surfaces, achieving shapes of quality.
- Software widely used worldwide by numerous companies.

Table 1. Catia V5R19 Accuracy.

Scale Work range	Maximum accuracy	Maximum range
Small Scale	0.01 micron	1m
Standard Scale	1 micron	1 km
Large Scale	0.1 mm	100 km

### Design description

With the aim at mounting turbines with a varying number of blades, we have designed 3 types of 60 mm diameter wheels that allow to mount between 2 and 8 supporting devices for the blades; you can view Fig. 2.

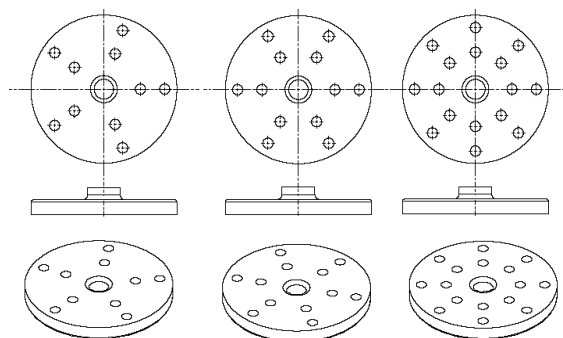


Fig. 2. Wheels designed for the mount of a variable number of blades.

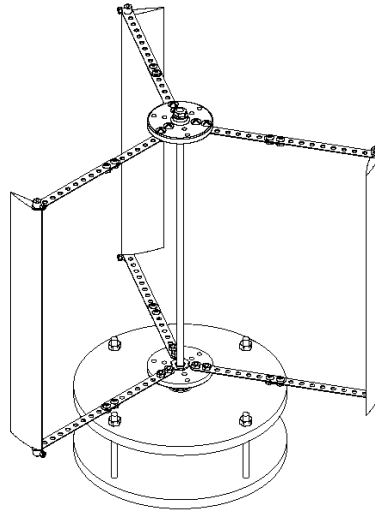


Fig. 3. Prototype general view

Regarding the blades, we have chosen symmetric NACA profiles, since they have been proven to be the most suitable for Darrieus-type wind turbines [7]. More precisely, we have designed the blades using the profiles described in Table 2.

Table 2. NACA profiles used.

NACA 0012	NACA 0015	NACA 0018	NACA 0021
Blade Chord length: 30, 40, 50 mm	Blade Chord length: 30, 40, 50 mm	Blade Chord length: 30, 40, 50 mm	Blade Chord length: 30, 40, 50 mm

In particular, blades have been conceived to be used for a straight type VAWT, i.e. we have considered straight cylindrical elements, parallel to the vertical axis, for each NACA section. These sections count with a height of 270 mm, divided into two 135 mm halves, in order to accomplish with the size constraints imposed by the BCN3d Printer. Besides, some standardized commercial elements have been included in the prototype design; see Table 5.

As far as the blade supporting arms are concerned, they have been built by joining two strips of 90 and 110 mm respectively, obtaining this way a variation in the rotation radius ranging from 45 to 175 mm, with 10 mm increments, since these strips counts with 4 mm diameter holes, whose centers are located 10 mm away from each other's.

Furthermore, we have designed a supporting device with two circular 19,5 mm diameter basis, which are mounted 6 cm away from each other. They allow not only an easy introduction in the tunnel, but more importantly, a smooth vertical spin of the turbine axis (by means of two 22 mm diameter bearings). The turbine axle is 390 mm high, and, in order to simplify the installation, consists of a metric 6 screwed bar. The assembly is depicted in Fig. 3.

### Rapid prototyping via FDM

According to the design discussed in Section 2, blades and wheels are the only non-standard components, which help to manage solidity and efficiency as well. These are potentially the elements with the greatest manufacturing cost and therefore our candidates to be printed using a rapid prototyping technique.

Fused Deposition Modelling (FDM) is an additive technology where a plastic material (usually PLA or ABS) is fused and extruded through a nozzle. This nozzle, ruled by a CNC program, fills layer by layer the volume of a component. FDM technology was developed in the early nineties and nowadays it has become the most commonly

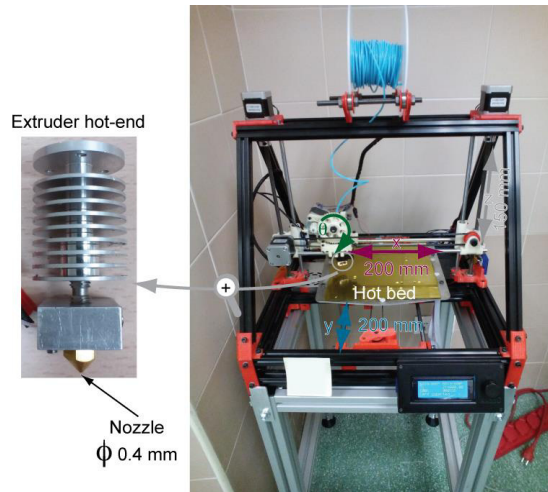


Fig. 4. Main characteristics of the 3D printed used

used Additive Manufacturing (AM) technique.

Gibson et al. [10] point out the characteristics of FDM technology. Regarding the advantages:

- Wide range of materials.
- Adequate mechanical properties; FDM provides stronger polymer parts than other AM processes.
- Low cost machines and materials compared to other AM processes.

The nozzle head inertia limits its acceleration leading to the main FDM disadvantage: a low operation speed.

#### *FDM printer characteristics*

Blades and wheels are printed in a BCN3D machine, Fig. 4. This printer is based on rebrap project, which provides hardware designs and software to control different printer variants [11]. These machines can be assembled with minimum cost and tools. An assembled machine, similar to the BCN3D model, costs around 900 €.

#### *G-code generation*

We have to define the printer parameters to control part finishing. The printer runs a G-code program, which includes parameter values and the extruder path. There are several applications that provide automatically the previous G-code from an STL version of a CAD file.

Because of its simple interface and its accessibility (it is an open-source application), we have used Repetier host to define the main printing parameters and to get the G-code program. It shows the interface of this package and its main tools such as visualization, object placement, slice and G-code generation, and manual printer control.

The input to Repetier software is a part or model in StereoLithography STL format. It is a discretized version of the original CAD model. We convert blades and wheel CAD model into STL format with a maximum deviation of 0.007 mm.

Regarding slice and G-code generation, Repetier uses Slicer plugin, which slices the object and generates the G-code to print a part according the user parameter definitions. Table 1 shows the selected values for the main process parameters.

An example of the G-code generated, and the simulated layer deposition for the wheel part is shown at Fig. 5.

After testing a set of parameter values, we observe that those of Table 3 provide adequate part finishing, shape and dimensions in a reasonable time (always lower than 3 hours/part). Note that layer height is probably the most important variable because it influences the number of layers (and therefore printing time) and the part roughness. Fig. 6, shows the differences between 0.2 mm and 0.4 mm layer heights.

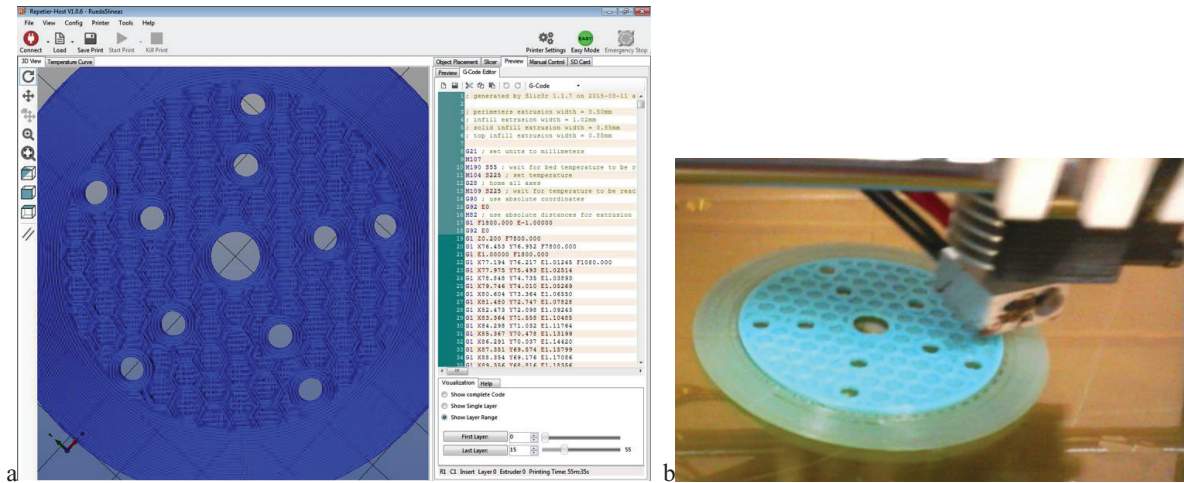


Fig. 5. (a) G-code generated and deposited filament for layer 0 through layer 15; (b) actual piece during printing.

Table 3. Main printing parameter values.

Property	Wheels	Blades
STL deviation (mm)		0.007
Material		PLA
Layer height (mm)		0.2
Temperature Hot-end (°C)		225
Temperature Hot-bed (°C)		55
Infill (mm)	0.4	0.8
Fill pattern	Honeycomb	Rectilinear

**Main steps for FDM printing**

INPUT: a STL file with the discretization of the CAD model of our goal component. For high quality reduce the deviation between CAD model and STL version increasing the number of triangles.

Add the STL piece into Repetier or similar software and configure the printing parameters such as layer height, temperature, feed rate etc.

Automatically slice and generate the G-code to control the process.

Send and run the aforementioned G-code in the 3D printer.

**Developed prototype**

This section is devoted to present the assembled VAWT prototype. Fig. 7 shows the actual mockup and the CATIA design. Note that, the assembly is straightforward and the number of components is low. Moreover, we have

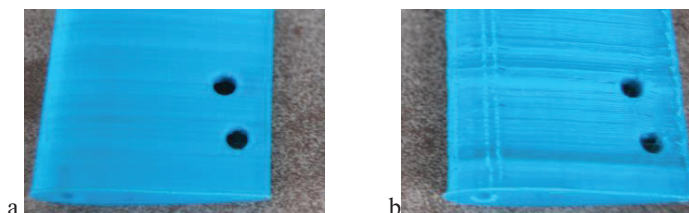


Fig. 6. Blade printed with a layer height of: (a) 0.2 mm; (b) 0.4 mm.

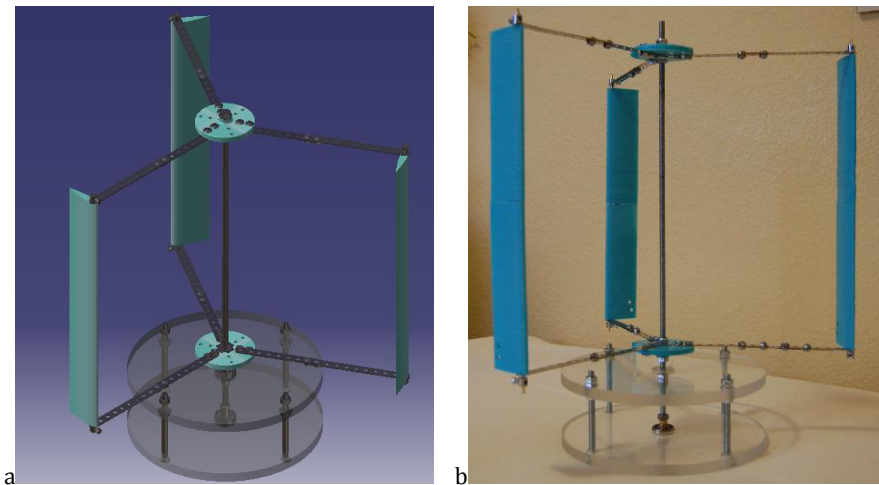


Fig. 7. (a) Catia design; (b) actual mockup

Table 4. Measured parameters of printed pieces. Blades 1-3 &amp; wheels 1-2 were chosen for our prototype (Fig. 8)

		Height (mm)	Width (mm)	Weight (g)	Roughness ( $\mu\text{m}$ )	Material Cost (€)	Layer Height (mm)	Printing Time (hours:min)
Blade: Height 270 mm, Width 7 mm	Blade 1	269.09	6.94	44	13.268	0.90	0.2	6:00
	Blade 2	269.05	6.87	44	14.292	0.90	0.2	6:00
	Blade 3	269.68	7.00	46	13.382	0.92	0.2	6:00
	Blade 4	269.64	7.42	52	26.861	1.04	0.4	3:00
	Blade 5	269.09	7.49	48	31.72	0.96	0.4	3:00
	Blade 6	269.52	7.37	50	31.282	1.00	0.4	3:00
		Diameter(mm)	Thickness(mm)					
Wheel: Diameter 60 mm, Thickness 6 mm	Wheel 1	59.20	6.04	11		0.22	0.2	1:00
	Wheel 2	59.32	6.06	10		0.20	0.2	0:30
	Wheel 3	59.31	5.89	12		0.24	0.4	0:30

measured a set of parameters in order to get an idea of the used printer limits. Table 4 portrays those measurements.

The deviation between nominal and actual dimensions are less than 1% for those parts printed with a layer height of 0.2 mm. Regarding the cost, we have estimated the material cost from the part weight, so that biggest components (blades) cost around 0.9 €. The most expensive components are the bearings, which are priced at 9 euros each one. The Table 5 shows the prototype cost depending on blades number.

## Conclusions

Summarizing, this work presents a product development method based on FDM rapid prototyping, and applied to produce scaled Vertical Wind Turbines VAWT. The great cost of experimental VAWT can impede to open the research about this technology. Low cost prototypes as the presented here can contribute to overcome this drawback.

Most components of our design are standard part. Non-standard components (blades and wheels) are developed in other to test its influence in the system behaviour. In order to test the influence of different solidity values in VAWT performance, FDM technique has been used to manufacture blades and wheels components.

FDM is a low cost and flexible additive manufacturing technology. Printing process can be performed almost automatically. There are several software solutions to transform a CAD model in STL format to the necessary g-

code. We use the open-source program Repetier, which slices and generates a G-code file with the user preferences. Printer parameters have to be adjusted in order to get an adequate result. The layer height is the main parameter affecting surface finishing.

Some parameters related to the non-standard components printing process have been measured in order to illustrate the capabilities of the method. Those parameters are: height, weight, roughness, printing time, energy and raw material cost. All parameters results support the feasibility of the proposed methodology.

Table 5. Prototype cost depending on blades number

Component	Items	€/ud	Blades number							
			2	3	4	5	6	7	8	
Bolt M6 Height 80mm + Nut M6	4	0.27	1.08	1.08	1.08	1.08	1.08	1.08	1.08	
Nut M6 with Collar	4	0.18	0.72	0.72	0.72	0.72	0.72	0.72	0.72	
Tread 608.2RS	2	9.5	19.00	19.00	19.00	19.00	19.00	19.00	19.00	
Methacrilate A3 sheet 10mm	1	12	12.00	12.00	12.00	12.00	12.00	12.00	12.00	
Threaded Axle 6mm	395mm	1.02	0.40	0.40	0.40	0.40	0.40	0.40	0.40	
Nut M6 with Collar	2	0.18	0.36	0.36	0.36	0.36	0.36	0.36	0.36	
Nut M6 autoblock	2	0.25	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
Brass split anchor	2	0.25	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
Threaded nut with spines	6	0.47	2.82	2.82	2.82	2.82	2.82	2.82	2.82	
Bolt M4 12mm Height + Nut M4	4*Blades number	0.26	2.08	3.12	4.16	5.20	6.24	7.28	8.32	
Strip 90mm	2*Blades number	0.4	1.60	2.40	3.20	4.00	4.80	5.60	6.40	
Strip 110mm	2*Blades number	0.5	2.00	3.00	4.00	5.00	6.00	7.00	8.00	
Bolt M4 8mm (Allen) + Nut M4	4*Blades number	0.25	1.00	1.50	2.00	2.50	3.00	3.50	4.00	
Brass 2mm tube	290mm *Blades n	2.7	1.57	2.35	3.13	3.92	4.70	5.48	6.26	
Wire rope clip	2*Blades number	0.93	3.72	5.58	7.44	9.30	11.16	13.02	14.88	
Wheels (raw material)	6	0.24	1.44	1.44	1.44	1.44	1.44	1.44	1.44	
Blades (raw material)	-	0.9	1.80	2.70	3.60	4.50	5.40	6.30	7.20	
Prototype cost (without labor) €			52.59	59.47	66.35	73.24	80.12	87.00	93.89	

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