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Manufacture and experimental evaluation of a hydrokinetic turbine for remote communities in Colombia

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Abstract. The manufacture and experimental evaluation of a hydrokinetic turbine of 1 kW are presented. A water velocity of 1.5 m/s, with a power coefficient of 0.4382, a tip speed ratio of 6.325, an angle of attack and pitch angle of 5 and 0 degrees, respectively, a blade length of 0.79 m, a drive train efficiency of 70% and a S822 hydrofoil profile were used for the design.
The blades were designed and manufactured by Computer Aided Design (CAD) and Computer Aided Manufacturing techniques (CAM) with a solid cross-section in order to provide the required strength. They were made of Prolon MS (Castnylon + Molybdenum). The platform that supports the turbine was a modular floating raft simple to install, flexible, and durable made of high density polyethylene resin. The supporting structure of the turbine generator was made of stainless steel. The turbine was constructed of high quality and durable materials.
To determine the efficiency of the designed turbine, the electrical power and kinetic energy of the river were measured. The experimental assays of the turbine were performed in the Sinú River located in Córdoba (Colombia), obtaining an overall equipment efficiency of 0.5359.

Key words: Hydrokinetic turbine, power coefficient, blade, hydrofoil

1. Introduction

Although, Colombia has a clean electricity generation matrix, and about 68% of its installed capacity comes from small and large scale hydropowers. The energy production diversification including renewable resources has been a popular topic of discussion in recent years due to international policies and concerns on environmental issues. Therefore, in Colombia during the last years, solar, biomass, and wind, among others, have emerged as new clean and non-conventional energy resources for the diversification of the energy basket and for the energy supply of the Non-Interconnected Zones (NIZs) [1].

For all purposes related to the provision of energy public services, it is understood that NIZs include all municipalities, townships, towns, and hamlets not interconnected to the National Interconnected System (NIS). In Colombia this area represents 52% of the total land of the country, but has only 5% of the population. Generally, NIZs are located in remote areas with difficult geographical and natural conditions making the need to generate energy locally. Most of the electricity supply in NIZs comes from diesel generators or small scale renewable energy systems, such as photovoltaic; however, these areas still have good natural resources, which have not been exploited for generating electrical energy. Indeed, the government of Colombia; in special, the Ministry of Mine and Energy considers that energy efficiency, investment in clean technology and in renewable sources of energy should be the premise of the energy policy for the future in Colombia.

Over the last few years, the use of kinetic energy from the flow of water in rivers, channels, tidal and ocean currents is considered to be an alternative or non-conventional form to generate electricity using hydrokinetic turbines. This technology is an advance in relation to environmental impacts for it is not necessary to store the potential energy in artificial lakes with the use of water dam, and so it consequently does not need to interfere with the natural course of rivers [2]-[6].

Hydrokinetic turbines, although constitute an immature technology that is still in the development stage, they can be adequate to decentralized generation once they are indicated for the assistance of small isolated riverside communities in the NIZs in Colombia due to their high energy density, good predictability and minimal environmental impact. Additionally, they might present robust design and ease of installation and maintenance [1]. It is important to note that remote communities often require electricity for small loads such as lighting, refrigeration, communications etc., which could be provided by hydrokinetic turbines.

Under this scenario, the focus of this paper is to describe the manufacture and experimental evaluation of a hydrokinetic turbine of 1 kW to be used in off-grid remote communities in Colombia or developing countries for satisfying their electricity demand. The design of the blades is based on the Blade Element Moment (BEM) theory to keep the stress at a safe level, eliminating the possibility of an excessive distortion or fracture during their operation. For the manufacturing process, a general methodology was developed using Computer Aided Design and Computer Aided Manufacturing techniques (CAD/CAM).

2. Model of the hydrokinetic turbine

The hydrokinetic turbine consists of several components shown in Fig. 1 however the most important component that has a large effect on the overall power produced is the rotor. In general, a rotor consists of blades connected to a central hub that ultimately provides the shaft to transmit torque to the system. The blade design needs to be carefully considered due to the effect it has on the power coefficient. This implies that there is an optimum design for a given flow rate, or a maximum increase in the power efficiency due to a maximal and a minimal increase in the lift and drag forces, respectively [2], [3].

In general, varying hydrokinetic loadings, water/mud corrosion and impact from floaters and fish schools each has a significant effect on the blade's operating life. From a structural point of view: 1) the hydrokinetic turbine blade is long and flexible; 2) there are possibilities of vibrations in the resonant mode; 3) the randomness of water velocity causes the randomness of load spectra; 4) low maintenance is expected during the operation under water with different conditions. Load identification, geometry/structural design, static failure, and fatigue failure need to be addressed to create a successful blade design [2]-[5].

Hydrokinetic technology shares a lot of similarities with wind turbine systems in terms of physical operation principles, electrical hardware, and variable speed capability for optimal energy extraction [6]-[8]. The advantage is that water is denser than air, hence it extracts enough energy even at low speed. The design of an optimum blade is achieved using the Actuator Disk theory and the BEM [9]; therefore, in order to calculate the geometry of the blade, the power of the turbine was fixed at 1 kW, the water velocity was 1.5 m/s, the power coefficient was 0.4382, the tip speed ratio was 6.325, the angle of attack and pitch angle were 5 and 0 degrees, respectively, and the overall transmissions efficiency including the mechanical transmission and the electrical conversion was assumed to be 70% [10]-[12].

For these conditions, the length of the blade, chord length distribution and the twist distribution along the blade length were calculated. The detailed calculation procedure can be consulted in the references [10]-[12]. The length of the blade was equal to 0.79 m and with a maximum width of 0.381 m. The rectangular root section of the blade was designed for an easy mounting on the hub. The blade consisted of 10 blade stations. The blade profile was based on hydrofoil S822. The hydrofoil provided a high ratio of lift coefficient/drag coefficient. This hydrofoil profile was developed under a joint effort between the National Renewable Energy Laboratory and Airfoils, Inc. It was specially tailored for using on small horizontal axis turbines. The hydrofoil has several advantages over those hydrofoils traditionally used on aircraft. Firstly, hydrofoils have reduced roughness sensitivity for improving the energy capture under dirty blade conditions, owing to the accumulation of insect debris. Secondly, the increased section thickness of the root (S822, 16%) and tip hydrofoil allows for a lower blade weight, lower cost, increased stiffness, and improved fatigue resistance. Finite Element Method (FEM) was used to identify the turbine blade critical stress spots. It was also used to evaluate the blade structural failure. The results can be consulted in the references [10]-[12]. From the observed results concerning the numerical simulation, it can be indicated that neither the yield strength nor the tensile strength of the material were reached. The maximum stress was given for the root of the blade, with 2.3228 MPa which is about 1.71% of the material yield strength [10]-[12].

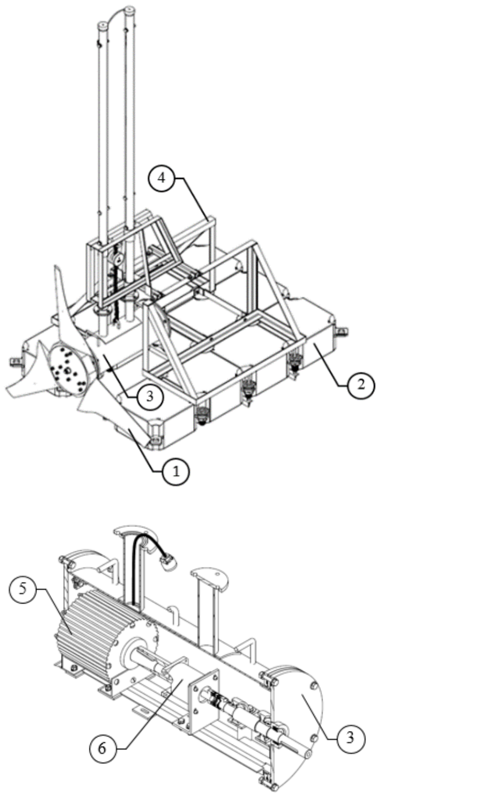


Fig. 1. Hydrokinetic turbine. 1-Blades, 2-Modular floating raft, 3-Generator housing, 4-Supporting structure, 5-Generator, 6-Gearbox.

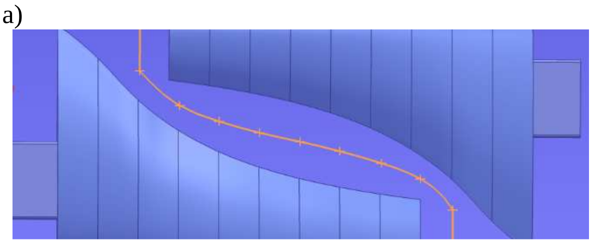
3. Manufacture of the hydrokinetic turbine

The blades of the hydrokinetic turbine were manufactured accurately and economically with the use of a CNC machining center. In order to be able to manufacture each blade, a number of conditions must be taken into account. First of all, the geometry of the part and the appropriate tools for the machining of the surface have to be selected so that the tools cutting surface are able to manufacture and remove material from the specific geometric places. Secondly, the tools must be constantly in contact with the surface, so as to manufacture it smoothly and accurately. Thirdly, the radius of the tool surface must be calculated so that the curves of the blade surface are correctly manufactured. Finally, the forth condition is the position of the cutting tool at the surface in order to appropriately manufacture the stock and prevent from any fault positioning.

For the blade manufacturing, the CAD file was imported in CAM software Nx for further analysis. With the aid of this software, the strategy of the blades manufacturing was decided and programmed with respect to the quality of the final product, addressed through a parameter of great importance, namely surface roughness and the required machining time. The manufacturing process took place in a CNC machining center Milltronics VM20 with four axes indexed. The tools used were a flat end mill of diameter equal to 25.4 mm and two ball end mills tool with 12 mm and 8 mm of diameter. The workpiece material employed was Prolon MS (Castnylon + Molybdenum). Taking into account the geometry of the blade, the strategy that has to be followed during roughing and finishing procedure was decided.

Initially, due to the high cost of this material, the geometry of the prolon billet was optimized to reduce wastes. For this purpose, a plate allowing two blades machining was taken as reference. For this reason, the first step was to separate the billet machining of each blade, as shown in Fig. 2a. This operation was carried out by designing a sketch to define the path of the cutter to cut the material. From this line, a profile of operation was performed, as presented in Fig. 2b.

a)



b)

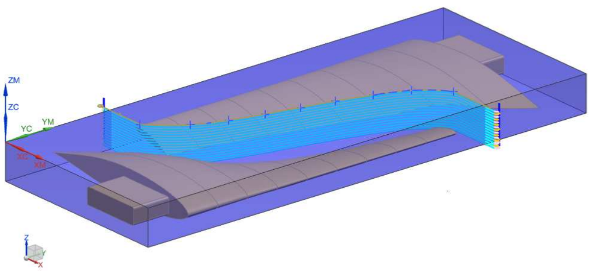


Fig. 2. Processes for cutting the prolon billet. a) Assemble and sketch, b) Simulation paths for cutting.

Due to size limitations of the bench, the process was conducted with the fixed billet at the table of the machining center without the use of the fourth axis. Machining on each side, the part was manually rotated; where, to ensure zero workpiece during rotation, they were fixed to the table three (3) records in steel, before the machining, as shown in Fig. 3.

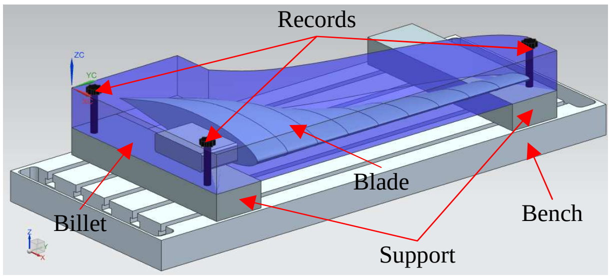


Fig. 3. Assembly of the turbine manufacturing process.

Two roughing steps and one finishing step were selected. In the first roughing step, higher depth or cut was used in order to reduce the machining time, while in the second roughing step, finer cutting conditions were used to prepare the material for the finishing operation. The latter gave to the blade the high quality characteristics that it requires to be operational. For roughing and finishing, three possible tool trajectories could be selected, namely cyclic, spiral or plain straight lines. The analysis showed that spiral movements of the tool gave better results at acceptable time, both for roughing and finishing operations.

Furthermore, in relation to the workpiece material machining conditions; i.e., cutting speed, feed rate and depth of cut, were chosen after many combinations performed with the CAM tools, so as to have a smooth and clear final surface. The cutting parameters were calculated based on the equations (1) (2) (3) and are represented in the Table I.

$$n = \frac{v_c * 1000}{\pi * D_{cap}} \quad (1)$$

$$D_{cap} = \sqrt{Dc^2 - (Dc - 2.a_p)^2} \quad (2)$$

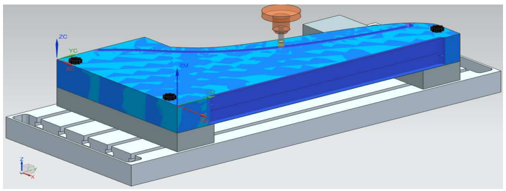
$$v_f = n * Z_n * f_z \quad (3)$$

where, v_c is the cutting speed (m/min), D_c is the diameter of the tool (mm), f_z is the feed per tooth (mm/tooth), n is the spindle speed (rpm), Z_n is the number of effective teeth, $D_{cap,}$ is the diameter at the depth of cut (mm), $a_{p:}$ is the depth of cut (mm) and v_f is the feed speed (mm/min). Both f_z and v_c are data provided by the tool manufacturer. The machining steps are presented in Fig. 4.

Table I. Machining cutting parameters of the blade.

Operation	Parameters	Value
First roughing	Cutting speed (mm /min)	2300
	Rotation speed (rpm)	4200
	Depth of cut (mm)	0.3
	Oversize (mm)	1.0
	Flat end mill (mm)	25.4
Second roughing	Cutting speed (mm /min)	1820
	Rotation speed (rpm)	6540
	Depth of cut (mm)	0.15
	Oversize (mm)	0.2
	Ball end mill (mm)	12
Finishing	Cutting speed (mm / min)	2053
	Rotation speed (rpm)	7000
	Depth of cut (mm)	0
	Oversize (mm)	0
	Ball end mill (mm)	8

a)



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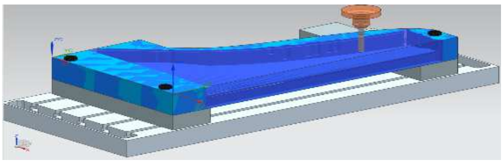

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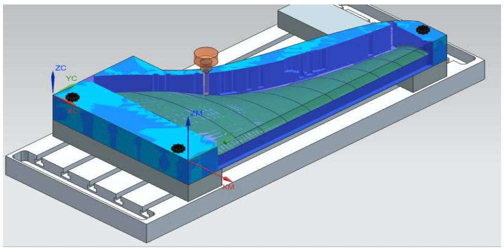

d)

Fig. 4. CAM software snapshots and real machining process. (a) roughing of the upper surface and blades with flat end tool (b) roughing of the blades (c) finishing of the blade with ball end tool and (d) finishing of the blades with ball end tool (real machining process).

Once the process was completed on the surface 1, the prolon billet was turned 180° for the machining of surface 2, for which the same strategy defined above was used. Finally, a profiling operation was performed to reach the final shape of the blade (Fig. 5).

Fig. 5. Blade of the hydrokinetic turbine manufactured by CNC

In general, the complex geometry of the blade, although is a challenge for the machining process, modern software and cutting and machine tools can overcome any problem imposed and realize the final workpiece geometry in relatively low machining times and with high quality characteristics.

Once the blades and the hub were made, the turbine was mounted on a frame with adjustable height, which was attached to a floating platform designed especially for this purpose. This floating platform consisted of a raft formed by several modular parts (Fig. 6) that provide unlimited configurations of the surface of floating; i.e., the floating cubes can be assembled to create the desired shape and size. The blocks were held together tightly and firmly with special connecting pins. All parts were lightweight and easy to handle. They were made or high density polyethylene resin. Candock cubes are remarkably resistant to impact, climate change and the adverse effects of water. The floating capacity of the surface formed was 680 kg, although the turbine and supporting structure alone weighed approximately 250 kg. In general, the floating raft provided a platform for operation and maintenance activities. The hydrostatic stability of the platform in static and towing conditions was studied for different positions of the turbine with respect to the water level.

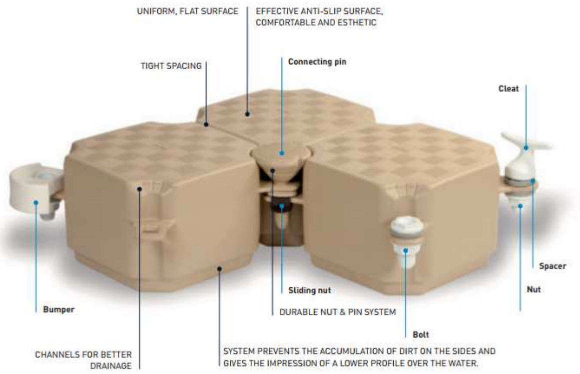

Fig. 6. Modular floating system. Candock (www.candock.com)

4. Experimental evaluation of the hydrokinetic turbine

It is well known that the best performance and the highest power production of the hydrokinetic turbine is made by a smooth linear flow of water at high velocity. The flow characteristic of a river stream has a stochastic variation, both seasonal and daily. Additionally, the water velocity varies from one potential site to the other depending on the cross-sectional area; therefore, the location of the turbine in the water current turbine must be very well considered.

The placement of the hydrokinetic turbine, in relation to the river cross-section, is a very significant component for two basic reasons. First of all, the energy flux in the surface of a stream is higher than that of the stream on the bottom. In addition, this quantity takes diverse values depending on the distance from the river bank [3]-[6]. The water current in a river may vary depending on the bottom. Therefore, the water velocity has a localized and site-specific profile, and the location of the rotor dictates the amount of energy that can be produced. Secondly, in a river there are competing users of the water stream, such as boats, fishing vessels, bridges, etc.; and these might reduce the effective usable area for a turbine installation [3], [5], [6]. There could also be varying types of suspended particles and materials like fish, rock, etc. in the river. In general, properly placing a hydrokinetic turbine requires an understanding of what influences the kinetic energy or velocity of the water at any point in the river.

The hydrokinetic system developed (Fig. 1) consists of a hydrokinetic turbine, gear, generator, power conversion interface and battery/grid. When the turbine is merged into the water, the flowing current turns the turbine, and the coupled generator rotor will spin along with the turbine shaft. If an induction machine is used as the generator, a gearbox is required between the generator and the turbine to produce the corresponding frequency during the lower water speed; nevertheless, the permanent magnet synchronous generator can connect to the hydrokinetic turbine directly. A gearbox system can provide machine noise, losses and increase the cost of the system for frequent maintenance. In addition, the gearbox also makes the hydrokinetic system more complicated with less reliability [3]-[6].

The output power is controlled and converted by power conversion interface. For a grid-connected system, an inverter connects to the DC bus to convert the DC power to AC power and exporting such as power to the power grid. For a stand-alone system, a load and a battery pack are attached to the DC bus. The resistive load is used to dissipate the extra power produced by the system when the battery is fully charge.

The performance of the hydrokinetic turbine designed was mainly characterized through the power coefficient (C_P) measurement. This Coefficient can be defined as ratio of output mechanical power of turbine (P) to the inlet kinetic energy of water per unit time or the total amount of the hydrokinetic energy that can be converted into mechanical energy by turbine. C_P can be calculated according to Eq. (4).

$$C_P = \frac{P}{0.5\rho\pi R^2 V^3} \qquad (4)$$

where $\boldsymbol{\rho}$ is the water density (997 kg/m^3), R is the turbine radius (0.79 m) and V is the flow velocity. The power coefficient refers to a measure of the blade or hydrofoil efficiency. It includes the hydrofoil shape and the hydrodynamic force of lift and drag. The electrical power output can be calculated according to Eq. (5) [10, 11, 12].

$$\mathrm{P}_e = \eta C_P 0.5\rho\pi R^2 V^3 \qquad (5)$$

The term η, is a measurement of the efficiency of the gearbox, drive train, the electrical inverter and the generator. This variable takes into account all the friction, slippage and heat losses associated with the internal mechanical and electrical components. Values of η may greatly differ among the different turbine models. The range of values of η are presented in the literature, highlighting the study conducted by Hangerman et al. 2006, which states a range of efficiencies between 95% to 98% [13]. However, for the design of the blade, a reasonable and conservative value of η around 70% was used [2, 10, 11, 12].

The product of the variables C_p and η is the overall equipment efficiency. For the measurement of this parameter, the turbine was paced in operation in the Sinú River, located in the state of Córdoba (Colombia). Initially, the turbine was transported to the site in the back of a pick-up truck (Fig. 7). A potential turbine site being accessible by road is a major advantage as it makes installation and maintenance a quick and easy process.

Fig. 7. Transport of the hydrokinetic turbine to the Sinú River.

Once the turbine was assembled on the river bank, it was towed to the final site of installation. The turbine was anchored to the river bottom using galvanized steel bars of 8 m in length (Fig. 8). Installation was completed in less than two hours, demonstrating the efficiency of the hydrokinetic installations. Smaller turbines, especially the portable turbines, should present fewer complications and result in even simpler installations.

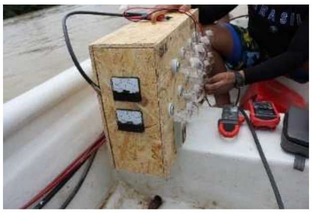

Fig. 8. Installation of the hydrokinetic turbine.

Once the turbine was installed, it was submerged in the stream of the Sinú River. For the installation of the submerged turbine, having enough width and depth of about 2 m is an important factor. The installation site had a depth of approximately 5 m. The turbine was installed in a region with a very constant river flow.

Once paced in operation, the power generated from the hydrokinetic turbine was transmitted to the power control center, which also contained a resistance bank (9 bulbs of 100 W each), and it was used as a load. Furthermore, a clamp current meter and a voltmeter were used to measure the power. The measurements did not provide significant results concerning the power generation due to the water velocity at the entrance of the turbine was only approximately 0.625 m/s; thus, the maximum power available in the water that can be transformed into electrical energy was 238.621 W. The turbine produced a maximum electrical power output of 127.89 W; therefore, the overall equipment efficiency was 0.5359.

Assuming that power coefficient of the turbine is the maximum theoretical power coefficient (C_{pmax}=16/27), the efficiency η of the turbine is 90.43%. On the other hand, if the power coefficient is equal to the value assumed for the design (0.4382), η is 73.94%. The turbine exhibited self-rotating characteristics whenever the water current speed crossed the cut-in speed of 0.625 m/s. Finally, the turbine was retrieved from the Sinú River after successful completion of the trial.

5. Conclusion

The hydrokinetic turbine designed to produce an electrical power output of 1 kW at approximately 1.5 m/s water current speed can provide a complete renewable energy solution for the remote communities in the developing countries. The developed technology is standardized and easily scalable. Qualified as a "green" technology, this product is positioned as the best alternative for decentralized electrification along rivers.

The turbine was rigorously tested in the Sinú River, located in Córdoba (Colombia). At this location, the turbine was suspended below the water surface from a special designed floating platform. The turbine was found to be self-starting at speeds near to 0.625 m/s. The overall equipment efficiency was estimated to be 0.5359.

During the designing process of the blade, it is essential to choose a simplified method construction, allowing making the blade locally in rural communities or near them for reducing turbine total costs. Technically, the turbine can be fabricated by a wide range of methods, ranging from hand carving up to CNC machine.

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