Mechanical Re-Design of a Wells Turbine Blade to improve the efficiency of the LIMPET Wave Energy Conversion System

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ABSTRACT

Renewable energies are told to be the future of energy generation for the world; nowadays, the wind sector is the one with more development in technology. However, there are two big sources of energy that have not been exploded to their maximum, not even on small percentage: sun and oceans energy. The sun is the biggest source of energy the planet counts with; but the second most important source of energy in the planet is the one produced by the motion of the oceans. A lack on technology is making it impossible to extract the energy from the seas.

Therefore, a mechanical re-design of a Wells turbine blade is proposed with the objective of developing new technology to convert oceans energy into electrical energy.

Keywords: Oscillating Water Column, Wells Turbine, SMA, Onyx, Nitinol.

1 INTRODUCTION

Mexico is a country with a vast variety of energy. Its energy generation includes non-renewable and renewable methods (Figure 1), such as: biomass and waste, coal, geothermal, natural gas, nuclear, oil and diesel, hydro, solar, and wind. Lately, the Mexican government is looking forward to invest in renewable energies in order to satisfy the existing and incremental demand for electricity. The main renewable energies the country is betting on are the solar and wind power generation. México's geographical location makes it ideal for renewable energy production; the country is among the top three countries in Latin America for both wind and solar potential [1]. Although having a big amount of wind-potential (an estimated of 50,000 MW) only 3,735 MW are transformed into electricity; this energy production represents a 5 percent of installed capacity in 2016 [1]. Solar power is other source of renewable energy the country is starting to invest on; it currently represents about 0.1 percent of México's total installed capacity.

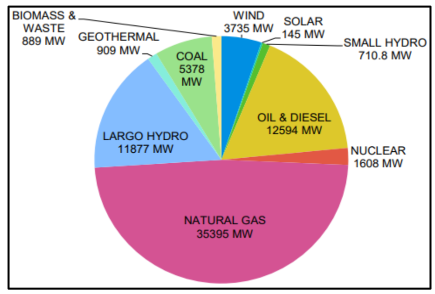


Figure 1. Mexico's installed power capacity by energy source in MW, 2016.

As mentioned before, the country's geographical location makes it ideal for exploiting natural resources; the average solar radiation range is about 5 to 6 KWh/m^2 per day, which doubles Germany's annual solar radiation (2.7 KWh/m^2), known for having the world's largest solar plant[1]. Therefore, the Mexican government has created many incentives to facilitate investment in both wind and solar renewables energies.

Despite the fact that México is investing in both wind and solar renewable technologies, there is one source of energy the country is not considering yet, and that is the oceans energy. As seen in Figure 2, México's land territory is surrounded by the two main oceans in the planet: the east-side coast faces the Atlantic Ocean with a length of 3,294 km, while the west-side coast faces the Pacific Ocean with a length of 7,828 km. Is estimated that the Mexican wave-potential is around 20-30 kW/m on the west coast, and 10-15 kW/m on the east coast (Figure 3).

In 2017, the Mexican Energy Innovation Center (CEMIE) and the National Council of Science and Technology (CONACYT) teamed up in order to promote the use of oceans-energy in México: tidal, salinity gradient, thermal gradient, seawater energy, and waves [2]. In the report "*Energía del* Oceano" (Ocean's Energy), written by the Secretary of Energy (SENER), a list of requirements is stablished to determine which of the mentioned technologies is suitable to work with.

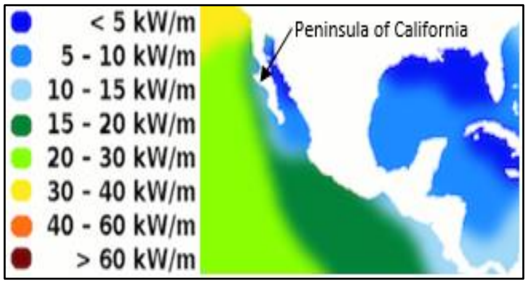


Figure 2 Mexico's potential wave energy measured in kilowatts per meter of wave crest. [https:// manoa.hawaii.edu]

This project focuses in the LIMPET 500, a device that converts wave-energy into electricity; this device is based in a oscillating water columns (OWC) method, which is a type of wave energy converter that harness energy from the oscillation of the water inside a chamber caused by the action of waves.

2 WAVE ENERGY CONVERTERS (WEC) FOR MEXICO

The Mexican Secretary of Energy established a set of goals in order to make it possible to install new renewable wave-energy converters in the country [2], from which the next three goals were selected to make a proper design:

- Identify geographical places with sufficient wave-potential to install such plants.
- Technologies
- Determine which materials are capable to withstand the oceans ambient.

With these goals established for considering wave-energy converters came up the idea of proposing a device like the LIMPET 500 as a possible prospect. This Wave Energy Converter (WEC), installed in island of Islay (Scotland), was the first device of its type to generate electrical energy and to be connected to an electrical distribution grid. The LIMPET is a shoreline device that uses oscillating water columns (OWC) to drive air in and out of a pressure chamber through a Wells turbine with a profile NACA0012 (symmetrical profile) [6].

Geographical Places

The main characteristic that a place must have in order to consider it as 'acceptable' to install an OWC shoreline-device is that a minimum of 20 kW/m power level from the waves is required [3].

As shown in Figure 2, the places with the highest wave-potential are located in the west coast, specifically in the states of: Oaxaca, Guerrero, Michoacán, Colima, Jalisco, Baja California (neighbor with California, U.S.), and Baja California Sur. The first five states mentioned before have a wave-potential in the range of 15-20 kW/m (dark-green area); this states have an acceptable potential to install WEC devices. Meanwhile, the states of Baja California and Baja California Sur count with different ranges of potential. The Gulf of California, which is on the east side of the Peninsula of California, has a range below 5kW/m (blue area), making it a poor place to install WEC devices; but the west side of the peninsula has a rage of 15-30 kW/m (dark and light green) along the Mexican shoreline [7].

A good place to consider installing WEC devices is Ensenada, Baja California. Pros of installing an OWC plant in this city are a wave-height average range of 1.5 – 2.5 m (H_{m0}^2) and periods of 12 seconds (T_e), which drops a potential range of 15 – 25 kW/m (Equation 1).

$$P = \left(0.5\frac{kW}{m^3 \cdot s}\right) H_{m0}^2 T_e$$

Equation 1. Wave energy flux. 'Wave Energy", Stanford University, 2010.

Another advantage is that Ensenada is home for one of the most prestigious investigation centers in Mexico, the Center for Scientific Research and Higher Education at Ensenada (CICESE, for its abbreviation in Spanish). Most of the activities developed by CICESE's investigators is collecting and processing data from natural phenomena, included oceans behavior. This would ensure data acquisition of high quality.

Finally, one of the difficulties the LIMPET device faced was the presence of extreme conditions of weather. Ensenada is a place with a low incidence of hurricanes, making it attractive to install shoreline devices.

Technologies

The purpose for this goal is to establish the basic elements of information about different existing technologies, inform the state of the art, and describe pros and cons [2].

Some reports [4] [5] concluded that OWC shoreline-devices, like the LIMPET, have the advantage of using Wells turbines as wind-receptor. A Wells turbine has the characteristic of rotating continuously in one direction independent of the direction of the airflow [4]. A disadvantage of Wells turbines is its operational airflow range; this varies depending on different variables: length, thickness, solidity, and materials. Wells turbines have a low starting factor [4] that could be improve with a variable pitch on the blades [3]; this would also increase its efficiency.

Materials Selection

An important aspect in the design of WEC devices is selecting materials with high durability, capable of work under high humidity levels, salinity and extreme environmental conditions [4]. The most common materials used in turbines construction are Titanium alloy class, GFRP class, and CFRP class. Studies from different authors show that the top materials to use are Fiber Reinforced Composites (Carbon Fiber/Epoxy Resin) and Titanium Alloys [4].

3 DESIGN OF A NEW BLADE

In order to increase the efficiency of the Wells turbine, a re-design of the blades is proposed; as mentioned by Shehata et al [4], a Wells turbine could increase its efficiency by adding a variable pitch.

To fulfill this need, the idea of a morphological structure capable of deforming itself emerged as an interesting and innovative solution.

Blade-Profile Design

A blade could increase its efficiency with a 7°-10° modification on its angle of trailing edge [5]. Therefore, the NACA0012 profile used in the LIMPET device was modify at in an angle of 10° (Figure 3).

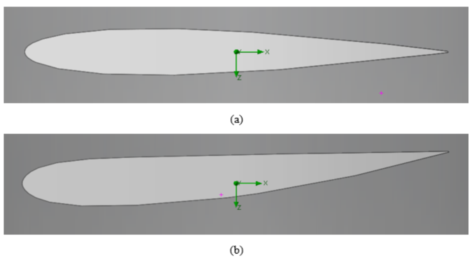


Figure 3. (a) NACA 0012 (b) NACA 0012 with 10° modification. Solidworks 2018.

A CFD analysis with airflows at 10m/s and 7m/s was made in order to compare the pressure profiles on the surfaces under the effect of the airflow. Figure 4 and Figure 5 show the results for the analysis; the pressure-profile in the original NACA0012 (Figure 4) is concentrated at 0.66 of the chord, where the highest pressure is expected to be [6], while in the one modified, a pressure-profile shows a bigger acting area (red), which could cause stalling.

For airflow at 7m/s (Figure 6 and Figure 7), results were a low-pressure profile for the original NACA0012, while the modified had a bigger pressure profile.

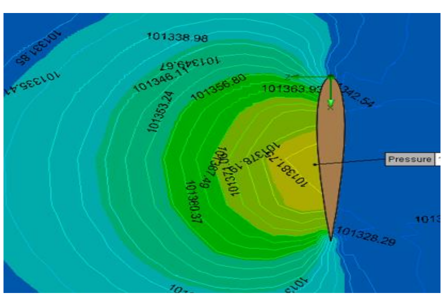


Figure 4. Airflow (10m/s) acting over NACA0012. Solidworks 2018 – Flow Simulation.

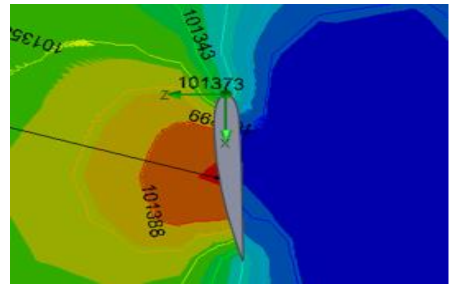


Figure 5. Airflow (10m/s) acting over NACA0012 with modified angle (10°). Solidworks 2018 – Flow Simulation.

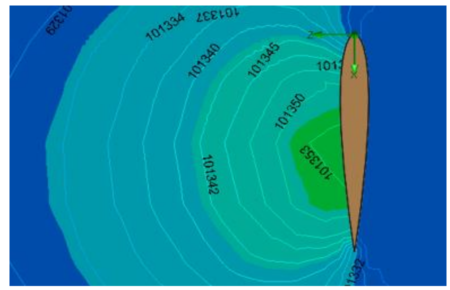


Figure 6. Airflow (7m/s) acting over NACA0012 (101353 Pa. Solidworks 2018 – Flow Simulation.

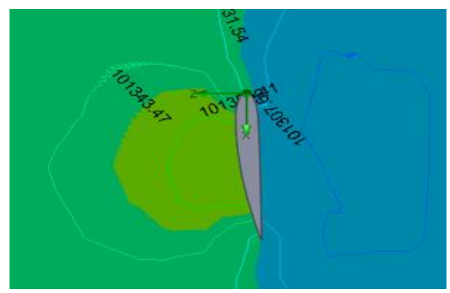


Figure 7. Airflow (7m/s) acting over NACA0012 Modified (101,391 Pa). Solidworks 2018 – Flow Simulation.

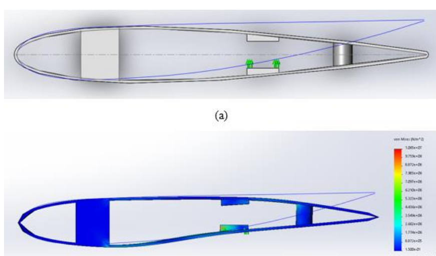
Materials

As mentioned before, Carbon Fiber and Titanium are the top materials for turbines. The material selected for making the proposed blade is called Onyx (Figure 8). Onyx is a remarkably though nylon that provides parts with stiffness equal to or greater than any pure thermoplastic material available for 3D printing. Onyx is a nylon thermoplastic infused with chopped carbon fibers.

Property	Test Standard	Onyx	Nylon
Tensile Strength (MPa)	ASTM D638	36	54
Tensile Modulus (GPa)	ASTM D638	1.4	0.94
Tensile Strain at Break (%)	ASTM D638	58	260
Flexural Strength (MPa)	ASTM D790*	81	32
Flexural Modulus (GPa)	ASTM D790*	2.9	0.84
Flexural Strain at Break (%)	ASTM D790*	N/A**	N/A**
Heat Deflection Temperature (°Celcius)	ASTM D648 Method B	145	44-50
Density (g/cm^3)	N/A	1.18	1.10

Figure 8. Onyx mechanical properties. Markforged: composites data sheet.

An important characteristic of this material is its tensile strain at break (58%). With such tensile strain, deforming the blade made of Onyx at 10° becomes possible. Figure 9 (a) shows the original position of the NACA0012 profile, and Figure 9 (b) shows the deformation when modifying the angle.



(a)

(b)

Figure 9. (a) Original NACA0012 profile, with a wall of thicknes = 2.5mm. (b) NACA0012 under actuators force (Von Misses = 10MPa). Solidworks – Simulation.

The Von Misses (N/m^2) was of 10 MPa, three times less than the maximum strength acceptable for deforming the material.

The actuators that are going to be used to make the displacement of the blade are made of nitinol (nickel titanium alloy) (Figure 10). Its shrinkable properties, and lightweight characteristics makes it a top selection to be the blade mechanism actuator.

Mechanical properties					
Young's modulus	ⓘ	28	-	41	GPa
Specific stiffness	ⓘ	4.31	-	6.32	MN.m/kg
Yield strength (elastic limit)	ⓘ	81	-	193	MPa
Tensile strength	ⓘ	1.09e3	-	1.25e3	MPa
Specific strength	ⓘ	12.5	-	29.7	kN.m/kg
Elongation	ⓘ	5	-	10	% strain
Flexural modulus	ⓘ	* 28	-	41	GPa
Flexural strength (modulus of rupture)	ⓘ	* 81	-	193	MPa
Shear modulus	ⓘ	* 10.6	-	15.3	GPa
Bulk modulus	ⓘ	* 26.2	-	42.3	GPa
Shape factor	ⓘ	1			
Hardness - Vickers	ⓘ	* 320	-	380	HV
Elastic stored energy (springs)	ⓘ	109	-	486	kJ/m^3
Fatigue strength at 10^7 cycles	ⓘ	* 41.5	-	50.2	MPa

Figure 10. Nitinol mechanical properties. CES Edupack 2018.

CONCLUSIONS

Mexico is a country with a beneficial geographical-location for harnessing natural energy, making it an important place to invest on; its latest Energy Reforms have been considering investing in the use of different renewable energy converters, where the wind and solar sectors are the main option. The Mexican government is also interested in harnessing energy from the oceans; therefore, the Secretary of Energy stated the goals that needed to be accomplish in order to install such technology.

The LIMPET is a device with high potential as a WEC, but it needs to be improved. The main component to be improved is its turbine (Wells turbine type). With the mechanical redesign proposed is possible to increase the efficiency of the turbine.

A blade with a structure made out of Onyx (nylon reinforced with carbon fiber) is a viable option thanks to its tensile strain at break of 58%, and a tensile strength of 38 MPa; a finite element analysis dropped a result of 10 MPa when modifying the trail-edge angle up to 10°. This movement would be actioned by nitinol wires, with a tensile strength of 1090 MPa and an elongation 5 – 10%.

Modifying the trail-edge angle 10° improves the surface-pressure profile, which can start rotation on a lower airflow range (from 10m/s to 7m/s). Starting rotation at low airflow rates can increase efficiency on a 5 – 10%.

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