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SEA CONDITIONS INFLUENCE ON SOLAR ENERGY HARVESTING

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Abstract. *Offshore monitoring operations are activities performed in the middle of the ocean. Qualified crews perform those activities and focus in two principal areas: commercial and rescue activities. However, the operational cost and risk of human accidents drastically limits the operating envelope of these activities. Due the large spectrum of operations in the offshore environment, there is a growing need of low cost Autonomous Systems for Offshore Monitoring (ASOM). These systems reduce operational cost and environmental impact. Generally ASOM's can be described as small unmanned vessels, similar in size to autonomous submersible vehicles (AUVS) or Gliders, however they behave like a boat and do not necessarily perform submerged operations. We introduced a study of solar power capture in ASOM vehicle, specifically; we performed an analysis of how the Brazil's sea condition influences the solar energy capture. The study used a prototype that simulates the wave conditions in offshore environment and compares it with a static solar panel. The preliminary results showed that the wave conditions could reduce the power capture in at least 1%, besides that, the result also pointed out that the ASOM orientation could reject the wave influence, therefore, control de ASOM position in a long term mission could impact positively and improve the solar energy harvesting.*

Keywords: *Offshore operations, Solar energy, Autonomous vehicles.*

1. INTRODUCTION

Offshore monitoring operations are traditionally carried out by vessels with highly qualified crews. This type of work is performed for civil and commercial purposes. One of the most common and relevant examples is the search for accident survivors, another one is the verification and control of operations in the offshore oil industry. The first cited example requires a system able to inspect large areas in ocean, while the second requires an equipment to remain in the same position for an extended period. However, the high cost and risk of accidents drastically limits the conditions that allow the use of this type of tool.

Due the large spectrum of operations in the offshore environment, there is a growing need of low cost Autonomous Systems for Offshore Monitoring (ASOM) as an vessel alternatives. These systems reduce operational cost and environmental impact, since they do not require a complex installation, human operator in field and anchor lines. Generally, ASOMs are described as small-unmanned vessels, similar in size to autonomous submersible vehicles (AUVS) or Gliders; however, they move like a boat and do not necessarily perform submerged operations.

ASOM's needs an efficient power management, especially for long operational missions, therefore, industry seeks to improve three principal lines: 1) Source of energy, 2) Equipment consumption and 3) Models to forecast energy generation. The first one includes the production of new and more powerful solar cells and ways to increase the solar panels efficient as discussed in (Righini *et al.*, 2017); the second one uses control techniques or mechanical models to improve the equipment consumption and the system hydrodynamics as way to reduce the need of energy to perform long displacements ((Bowen *et al.*, 2013), (Wang *et al.*, 2016)).

The third line of works focus on models that forecast energy harvesting; one example of this kind of work was developed by Griffin (Griffin and Wyatt, 2014) where a power generation model was introduced to predict the Solar Panel ROI (Return On Investment) based in their power generation, in addition, works as introduced by Sera (Sera *et al.*, 2007) shows the temperature impact and how it affects the panel behavior. However, all of this works are based on both onshore conditions and fixed panels, so didn't introduce a practical result for offshore scenario.

One work that first addressed this problem was developed by Dutra in (Dutra and Ramirez, 2008) where a AUV model was used to forecast a power generation on sea. All the work is based on a theoretical model of AUV movement and in the Panel efficiency. In the same way, this work focused in measure the sea influence on solar energy harvesting, including the wave frequency and amplitude, when compared with a fixed solar panel. This comparison of both panels is relevant due the fact that regular ASOM missions use assumptions based in fixed solar panels, neglecting the influence of sea state in the solar generation as observed in (Jalbert *et al.*, 2003); however, our preliminary results pointed out that the wave height and the ASOM orientation could impact the solar energy harvesting in negatively ways.

2. EXPERIMENTAL PROCEDURE

To perform the study of wave impact in the solar energy harvesting, the authors decided to simulate the sea wave as a sinusoidal wave at the same frequency that the principal frequency of the Brazil's seas conditions and replicated that using a mechanical prototype, then, an experimental layout was developed to verify the amount of energy that a solar panel in the sea could generate.

The experimental layout used for this work is presented in Fig. 1. The Mobile solar Panel (MSP) used a platform that was developed to simulated a sinusoidal wave, therefore, during the test only one sinusoidal wave is simulated. In addition, the layout has a fixed solar panel (FSP) that works as a control sample of the lectures and is located horizontally. To verify that both Solar panel behaves similar during the experiment, after simulated each sea condition, we reproduce a second test with both solar panels fixed harvesting the same amount of energy. We adopted a test protocol that limited the test time in 2 minutes in order to reproduce similar light conditions in a batch of tests.

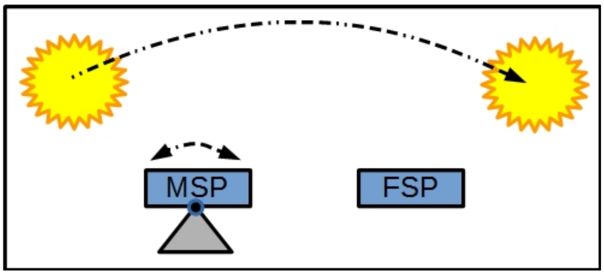

Figure 1. Experimental layout

2.1 Solar Panels

Two solar panels were used in this study. They are indeed for small applications and the authors would use them as a power source in a future prototype for autonomous offshore vehicle. They output 6V at 330 mA via 3.5mm x 1.1mm DC jack connector. The substrate is an aluminum / plastic composite, its size is 110mm x 140mm and its manufacturer claims around 20% efficiency. Figure. 2 shows a solar panel picture.

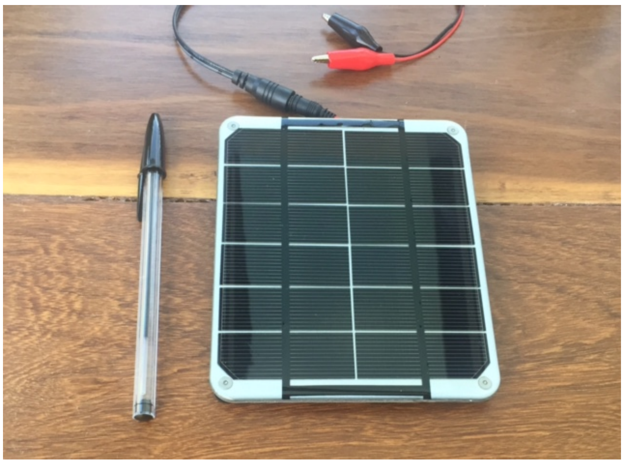

Figure 2. Solar panel, pen for scale purposes

Both panels were tested in different light conditions. In all tests were verified a small voltage difference between both panels under the same light conditions, therefore the panel with less voltage generation was selected as a fixed panel and the additional panel will work as a mobile panel.

In addition, the authors recorded the step response for the panels, the objective was to create a theoretical model of the light vs voltage generation of each panel, with the results was possible to identify the time constant τ of each solar panels and create a theoretical model. Figure 3 shows the step response of both panels and it is possible to observe the 0.2v difference between the fixed and mobile panel in steady state. The input step was creating putting the solar panels inside a box and suddenly open it. This test was performed indoor, so the solar panels didn't reach its maximum voltage generation capacity. Based on the results of Fig. 3 the time constant τ for the fixed and mobile panel was 0.24(s) and 0.27(s) respectively

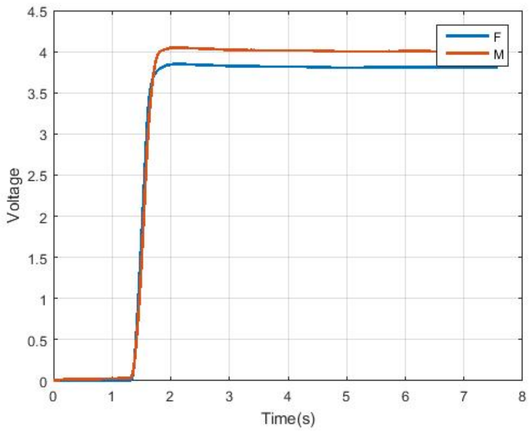

Figure 3. Step response of fixed (Fix) and Mobile (Mob)

The solar panel behavior observed in Fig. 3 allows the authors to confirm that the panels works as a first order linear systems with transfer functions $H(s)$ as described in Eq.(1), where K is the maximum amplitude in the steady state after step response (The manufacturer claims 6v for the panels used).

$$H(s) = \frac{K}{\tau s + 1} \tag{1}$$

The authors verify that the voltage difference drops from 0.2v until 0.016v at maximum level of light intensity. The test results are observed in Fig.4 where the panels reached a voltage generation above 6.45v in an outside test with noontime and blue sky condition. All the measurements were recorded using a analog to digital converter (ADC) of 10 bits, so the measurement resolution is 5mV.

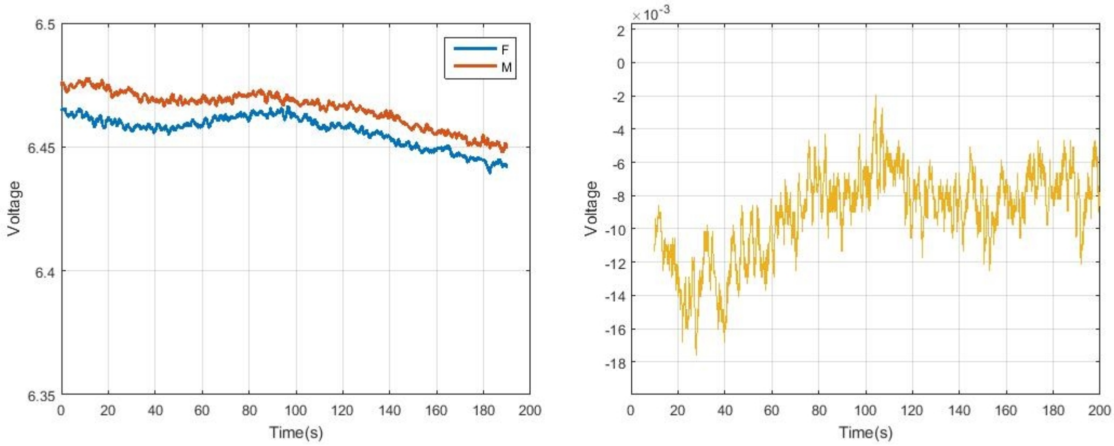

Figure 4. Voltage generated from solar panels and voltage difference

2.2 Sea spectrum

Sea's waves can be described as a combination of n number of sinusoidal waves with different magnitude and frequency, so the study of time responses in sea environments is not considered practical. However, the frequency response of ships and crafts is a traditional tool to define system behavior and to verify vessel stability. In order to identify an adequate combination of sinusoidal waves, researches have been working in sea wave spectrums than can be used as input for stability models.

One of the most used wave spectrum is the JONSWAP spectrum (Joint North Sea Wave Observation Project) . It was calculated based on North sea conditions, however, it is commonly used to simulate the Brazilian sea conditions (Nogueira, 2010). In addition to the JONSWAP Spectrum, the authors also study a second wave spectrum called Pierson-Moskowitz (PM), it was one of the first wave spectrum register in literature (Moskowitz, 1964) and was used in this study as a comparative model. Figure 5 shows the PM and JONSWAP spectrum, they have its maximum density in a range from 0.05Hz up to 0.1Hz and 0.2Hz up to 0.4Hz respectively.

In this work we are going to simulate two sinusoidal waves at 0.3Hz and 0.25Hz that are relevant frequencies in the JONSWAP spectrum for different sea conditions.

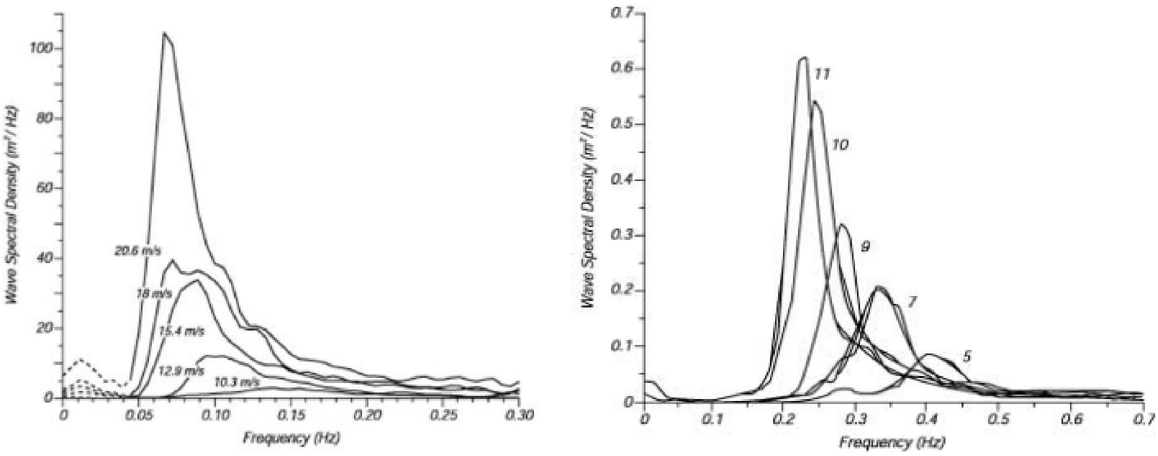

Figure 5. Pierson-Moskowitz (left) and JONSWAP (right) spectrum. Source:(Moskowitz, 1964)(Hasselmann *et al.*, 1973)

2.3 Mechanism for wave simulation

One simple mechanism was build to simulate a sinusoidal wave, It was made with recycle materials and projected to support the solar panel. Its maximum wave amplitude can be defined in four different values (15°, 20° and 30°); additional amplitudes will be include in future works after a mechanism improvement. Figure 6 shows the mechanism picture and its components (Motor, Ardunio Uno and Power circuit). Although the prototype is simple, it works close to the 0.3Hz and to 0.25Hz and can simulate satisfactorily a sinusoidal wave. Figure 7 shows the simulated wave at 20° and its frequency spectrum.

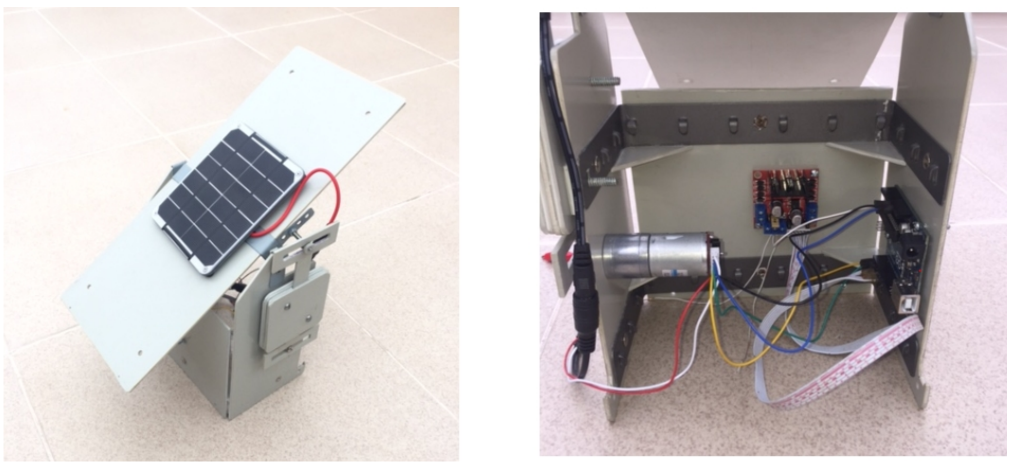

Figure 6. Mechanism (Left) and electronic components (Right)

3. RESULTS AND DISCUSSION

3.1 Sea Wave simulations

As observed in the previous section, sea waves can be defined as a combination of sinusoidal waves with different frequency and magnitude. In order to verify the effect of wave frequency on solar energy harvesting the authors decided to simulate the sea wave as one sinusoidal wave at the frequency 0.3Hz and 0.25Hz. These values were choose based on the JONSWAP spectrum as two principal wave frequencies, it is the frequency where sea wave spectrum has is maximum value for different wind conditions, so a sinusoidal wave at this frequency will be used as a sea wave representation.

For the tests, the three wave amplitude were simulated: 15°, 20° and 30°. The objective of this wave amplitude is to verify its influence in the solar energy harvesting. Figure 8 shows the voltage generated from the fixed (F) and mobile (M)

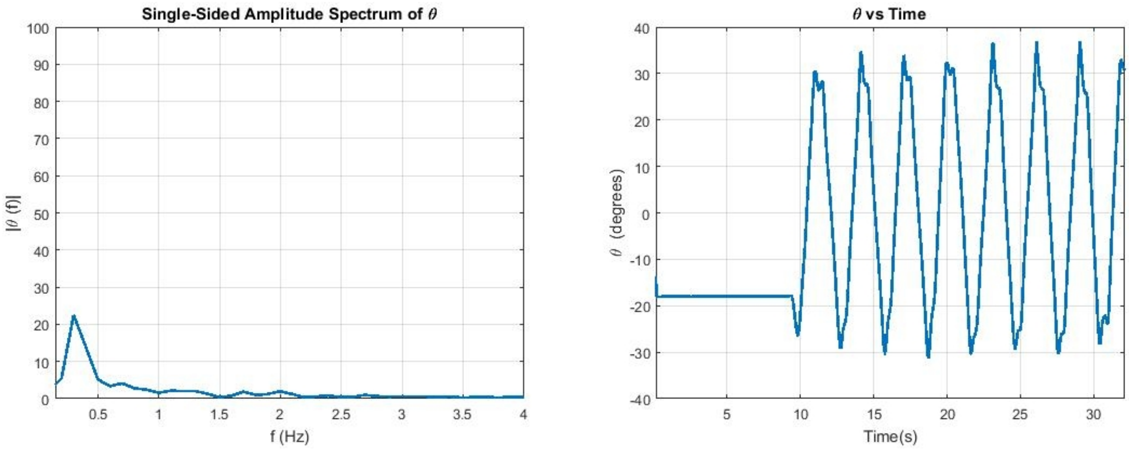

Figure 7. Frequency spectrum of the wave generated (Left), Wave generated (right)

solar panels. In addition, Fig 9 shows the simulation performed at 0.25Hz using the same wave amplitudes.

All the results were recorded outdoor and around noontime in order to guarantee that the wave simulator reach the maximum energy generation in the horizontal position, besides, the authors monitor the sun position and install the panels parallel to the solar trajectory as a way to mitigate its position influence on the results.

Table 1 and Tab.2 introduce a summary of the tests performed at 0.3Hz and 0.25Hz respectively, for different maximum angular position (θ) of the solar panel.

As observed the wave amplitude influences directly in the solar energy harvesting, In a parallel configuration, the wave of 30° reduce in 20mv the mean voltage generated of the mobile panel when compared with the fixed panel. In addition for lower wave amplitude 20° e 15° the mean voltage is 80mv and 40mv higher than the fixed panel.

In addition, Fig. 9, shows that the wave frequency doesn't affect the voltage generation behavior, so the results at 0.3Hz are similar than the ones recorded at 0.25Hz.

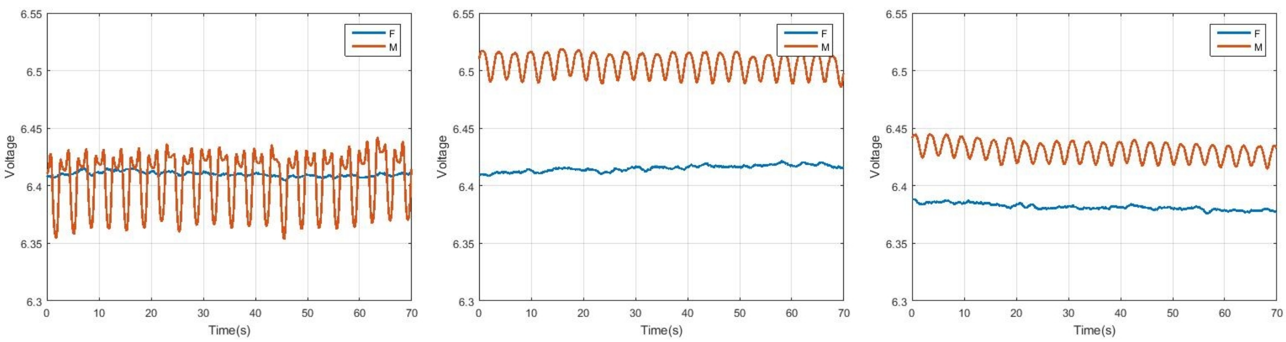

Figure 8. Test performed at 0.3Hz Right(A), Middle (B), Left (C)

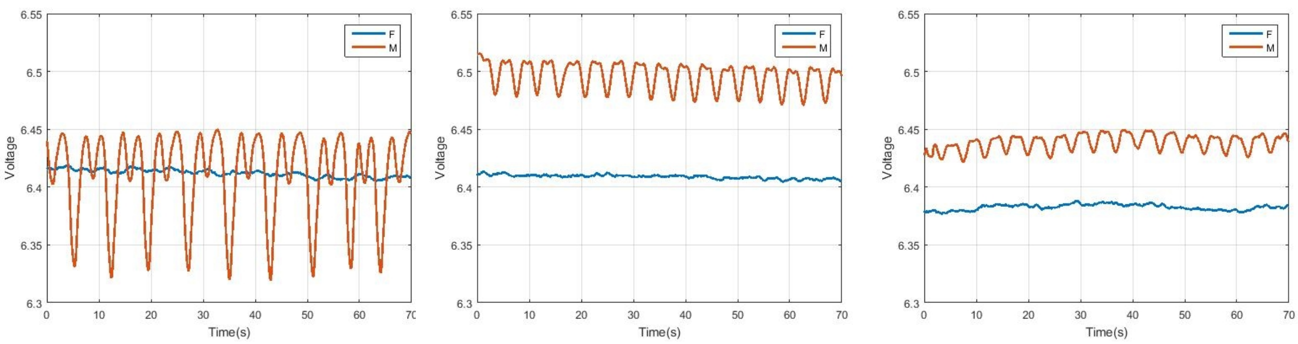

Figure 9. Test performed at 0.25Hz Right(D), Middle (E), Left (F)

The authors also tested the panel orientation influence on solar energy harvesting. The experimental setup changed and the panels were oriented perpendicular to the solar trajectory. Figure 10 shows the test results and the Tab. 3 shows the

Table 1. Mean voltage generation for 0.3Hz

Test ID	θ (degrees)	Mean voltage (m)	Mean voltage(f)	$\triangle$ voltage
A	15°	6.43	6.38	0.05
B	20°	6.50	6.41	0.09
C	30°	6.40	6.41	-0.01

Table 2. Mean voltage generation for 0.25Hz

Test ID	θ (degrees)	Mean voltage (m)	Mean voltage(f)	$\triangle$ voltage
D	15°	6.44	6.38	0.06
E	20°	6.49	6.40	0.09
F	30°	6.41	6.41	0

mean voltage recorded from the test. As observed the wave amplitude influences directly in the solar energy harvesting, specifically was measured an increase in 1% at the maximum θ amplitude.

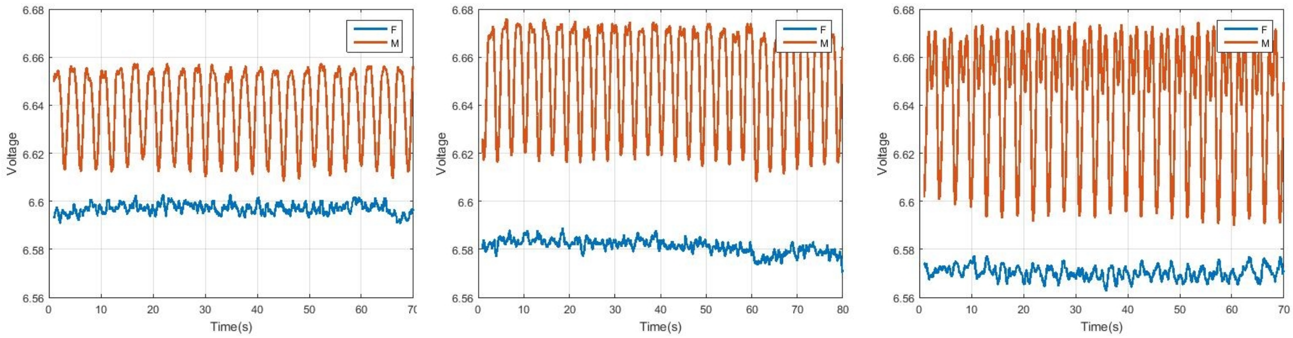

Figure 10. Test performed at 0.3Hz Left(G), Middle (H), Right (I). Perpendicular to solar trajectory

Table 3. Mean voltage generation for 0.3Hz Perpendicular to solar trajectory

Test ID	θ (degrees)	Mean voltage (m)	Mean voltage(f)	$\triangle$ voltage
G	15°	6.61	6.57	0.04
H	20°	6.63	6.56	0.06
I	30°	6.62	6.54	0.08

3.2 Conclusion

We performed and analyzed the sea condition impact in the solar energy harvesting. The study used a prototype that simulates one wave condition (three wave amplitudes and two principal frequencies) in offshore environment and compares it with a static solar panel placed in an horizontal position.

The tests showed that the wave conditions in a amplitude of 30° could decrease the power capture in at least 1%. In addition was observed that the voltage generation, in a parallel configuration is inversely related to the wave amplitude (See Test results A,B,C,D,E and F on Tab 1 and Tab 2), therefore, sea states with high waves could reduce the solar energy harvesting. To improve this results, the authors are working in new test with more wave amplitudes in order to extend the obtained results to more sea conditions.

In addition, was observed that the solar panel orientation has important influence on the solar energy harvesting. In a parallel configuration (Test A to F) increasing the wave amplitude reduces the energy harvesting, however in perpendicular configuration (Test G, H and I) the fact of increase the wave amplitude increases the energy harvesting, pointing out that the orientation of an autonomous vehicle could compensate the sea conditions effects, therefore, the orientation, as in onshore application, has an important impact on offshore solar harvesting .

Finally, as future works, authors would like to automatize the solar panel test. The objective is simulate more wave frequencies with a different range of wave amplitudes, this objective will achieve improving the angular velocity control and setting up a real time link between Matlab and Arduino. Besides that, perform this test in additional solar panels with different Time constants τ and efficiency will help to bring improved conclusions about the sea effect in the solar energy harvesting.

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