Experimental Validation of a Kinetic Energy Harvester Device for Oceanic Drifter Applications

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***Abstract*— A Kinetic Energy Harvester (KEH) device under design for drifter applications has been tested at real sea conditions in a controlled area. The KEH consists on a pendulum system capable to transform the oscillations of the waves into rotation which will be converted into electrical energy thanks to a dc micro generator. The KEH has been placed inside a drifter. First, the motion of the drifter was obtained through an embedded Inertial Measurement Unit, showing natural pendulum frequency of 1.5 Hz. Simulations with OrcaFlex validate the experimental results. Then, the rotation speed of the micro generator was measured. Results show a prevalence of speed of 1400 rpm, which should lead to a potential power output of 2 mW.**

Keywords*— Lagrangian Drifter, Kinetic Energy Harvester (KEH), Micro generator, Natural Frequency, Power Management Unit (PMU), Maximum Power Point Tracking (MPPT).

I. INTRODUCTION

Oceans are a key indicator on earth's health. Small changes on the seawater can strongly affect the weather, but also on many species' behaviors. Oceanographic monitoring becomes crucial in terms of understanding biological and meteorological changes. Many different sensor platforms fulfill this monitoring function. Seafloor cabled observatories, for example, can provide a huge volume of data from a specific underwater position with no power restrictions, while underwater gliders, as another example, cover large portions of the ocean providing smaller data products with some power constrains.

Lagrangian drifters are a low-cost easy-to-deploy solutions for sea monitoring. These are versatile and easy to maintain units that monitor the ocean while passively following the surface currents. Nevertheless, drifters do not offer a high volume of data compared to other platforms and power restrictions are higher. Applications where these platforms are used are diverse; climate research, oil spill tracking, weather forecasting and search and rescue operation. Lately, drifters have found a useful field of work, helping to calibrate HF radar and satellite measuring systems of sea surface parameters.

Autonomy is one of the main challenges at drifter design [1]. Depending on the carried instruments and the duty cycle of the units, its lifespan may vary from hours up to two years when powered from primary batteries. To expand its autonomy, some manufacturers include PV panels around drifters' body, achieving unlimited lifespan at some low transmitting interval and propitious solar conditions [2]–[5]. Nevertheless, if the drifter is strictly dedicated to the current monitoring, the body should be mostly submerged to avoid the wind effect [6] and, thus, the irradiation at the panels is attenuated. Also, many oceanic regions may provide really low solar irradiation at some year periods. For this reason, other Energy Harvester (EH) sources may be explored as the kinetic oscillatory movement of the waves.

Previous works have shown different harvesting possibilities from a kinetic ocean source [7]–[9]. Inertial based harvesters are one of the main solutions for non-anchored oceanic devices [10]–[13]. These systems relay on a proof mass whose relative movement is caused by the waves and drive a generator. The cleverness of these systems relay on achieving the resonant frequency of the Kinetic Energy Harvesting (KEH) near to the motion frequency of the drifter [14], to maximize the power extraction.

Figure 1. MELOA coastal WAVY drifter design for sea monitoring.

Scientific community has started to pay attention to the drifter development that includes alternative EH generation. The MELOA project [15] is an example of that. This is a European project that aims to develop a new family of WAVY drifters for marine monitoring which are low-cost, easily deployable, high

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versatility, and low maintenance systems. The WAVY family of products will include from coastal drifters for short deployments (Figure 1), to oceanic drifters with EH solutions for long term deployments.

This paper follows the work done at [16], where a first design of a kinetic energy harvesting to be placed on the oceanic MELOA drifter was presented. Also, a preliminary characterization of the micro generator and the Power Management Unit (PMU) was shown followed by the first results of the prototype when placed on a water tank.

Work presented in this paper is focused on characterizing the operation of an improved KEH when placed on a drifter under real sea conditions in a controlled area. The drifter has been designed with the same dimensions of the WAVY Ocean drifter of MELOA's project. In addition, the dynamic behavior of the drifter has been assessed with an Inertial Measurement Unit (IMU). Results have been validated with OrcaFlex simulation Software. Finally, the KEH power possibilities have been further analyzed.

The paper is organized as follows. First, the proposed KEH is presented at section II. Then, the materials and method are described in section III. At section IV, the results of the drifter motion and KEH behavior under real sea conditions are shown. Finally, conclusions are summarized at section V.

II. PROPOSED KINETIC ENERGY HARVESTER DEVICE

Harvesting the energy from the waves at non-anchored autonomous devices is usually done by inertial systems, which can be classified in gyroscopic and pendulum [17]. These systems relay on a proof mass which moves in relation to the main body thanks to the excitation of the waves. That relative motion drives a micro generator which converts the energy from mechanical to electrical. The difference between the gyroscopic and the pendulum systems bases basically on the way they capture the external motion. The first ones count on an inertial flywheel which continuously rotates by the external effect. At the second ones, a proof mass can be found outside the device at the end of an arm which pendulates.

The harvested energy depends on the physical characteristics of the devices, achieving higher power levels with higher sizes and weights. Also, this energy is directly proportional to the wave frequency and amplitude [18]. The resonant frequency of the KEH should be tuned to the frequency of motion of its carrier platform to maximize the power extraction.

Recently, we have designed and manufactured a first prototype of an inertial KEH for drifter applications [16]. This is a mixture of the gyroscopic and pendulum systems. It consists of three gyroscopic arms which capture the movement of all directions and excite a proof mass. This mass relatively moves respect the drifter with pendulum motion. Then, through a gear system, rotation is accumulated in a flying wheel which drives the dc micro generator. The gear system also increases the rotation velocity with a positive ratio. Thanks to a one-way gear system, the flying wheel only rotates at one angular direction at which energy is accumulated.

In this work, the device presented in [16] has been slightly modified. The three gyroscopic arms have been replaced by an articulated pendulum arm with a prof mass. Now, the relative motion is caused by the articulated arm that can freely rotate excited by the drifter motion. This drives the flywheel through the one-way gear system. Also, the Power Take Off (PTO) element is the same micro generator. This modification simplifies the device which can now be reduced and its power density increased. A 3D model of the modified design is shown at Figure 2 with the description of the different parts.

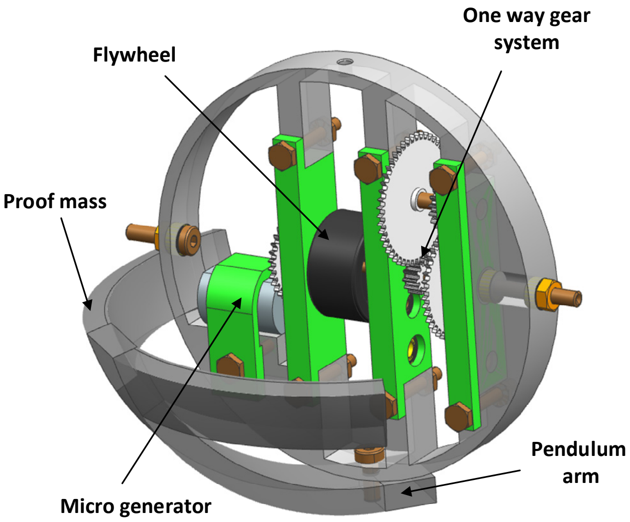

Figure 2. 3D model of the Kinetic Energy Harvesting (KEH) to be placed on a spherical drifter with the description of the different parts.

Figure 3 shows the manufactured prototype. It has a proof mass of 220 g and a total diameter of 10 cm. The main body has been 3D printed with polyamide and the proof mass made with lead. The total gear ratio is 35.

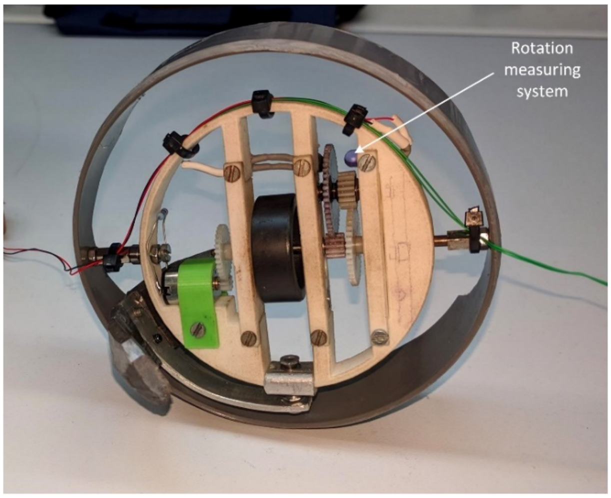

Figure 3. Image of the manufactured KEH prototype.

The dc micro generator has previously been characterized at different rotation speeds [16]. Figure 4 shows the results, where the rotation speed in rpm is defined with no load connected to the generator output (output voltage is V_{oc}). As can be seen, for the three curves, the Maximum Power Point (MPP) is found around half V_{oc}, which matches with the Thévenin model of the generator [19]. Furthermore, V_{oc} is directly proportional to the rotation speed and the maximum power is proportional to its square. The optimal load corresponding to the MPP is found around 18.5 Ω (R_{LOAD}), which should match with the internal generator load (R_G).

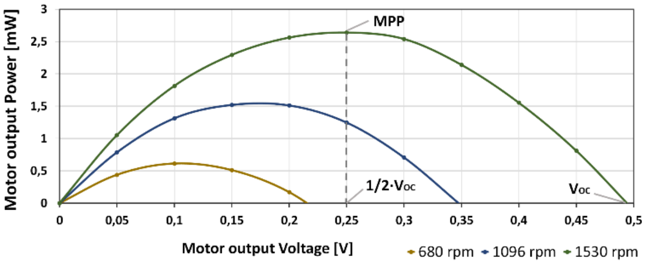

Figure 4. Generator output power against output voltage for different rotation velocities (determined at generator open circuit) [16].

III. MATERIALS AND METHOD

This work is divided in two objectives. On the one hand, study the motion of the drifter body in real sea conditions as well as determine its natural frequency. From this information, the resonant frequency of the KEH could be tuned in future designs to maximize the power extraction. On the other hand, corroborate the correct operation of the KEH under the excitation of wave motion by measuring the continuous rotation of the micro generator. It is important to verify that the KEH optimally converts the waves oscillation into usable rotation. In previous works we tested the device in a water tank [16] that emulates sea conditions, and the present work aims to experimentally validate it in the sea.

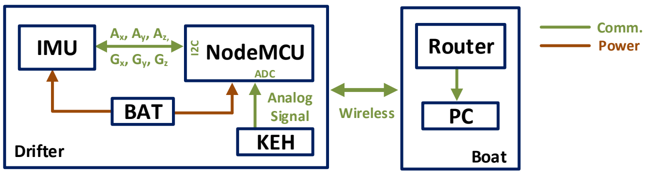

Figure 5. Experimental set up, with the different components placed on the drifter and on the boat, with its communication links.

Figure 5 shows the experimental set up, where the left box represents the drifter and the right box the boat. For this figure, brown has been used as power connections and green as communication links.

A WAVY ocean drifter from MELOA project with the parameters of TABLE I has been used with an Inertial Measurement Unit (IMU) placed on its mass center. This unit has provided the linear acceleration in the three axes (A_x, A_y, A_z) as well as the angular velocities data (G_x, G_y, G_z). Figure 13 presented later on this article shows the axes distribution.

TABLE I. Spherical WAVY ocean drifter parameters

Parameter	***Symbol***	***Value***	***Units***
Drifter mass	m_b	3.472	kg
Drifter radius	R	0.1	m
Center of mass[a]	c_m	0.06	m

[a] Center of mass taken from the bottom of the spherical drifter body.

The KEH has been placed on the geometric center of the drifter, above the IMU sensor. The micro generator has been connected to a constant load of 18.5 Ω, which is the optimum load found on its characterization. That condition would provide a resistive torque to the KEH.

As shown in Figure 3, an infrared emitter has been placed on the main body of the KEH pointing to a diode photoreceptor. Between them, one of the transmitting gears can be found with a hole placed on its circular surface. This gear is solidary to the micro generator so knowing the gear rotation the micro generator speed could be determined. Figure 6 shows the electrical scheme of the pair photo emitter-receiver. An Analog to Digital Converter (ADC) has measured he photodiode open voltage signal.

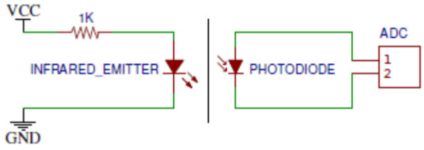

Figure 6. Electrical scheme of the pair photo emitter-receiver.

NodeMCU development board has been selected for its low-power consumption as the main control. It counts on a Wi-Fi communication module and is based on the ESP8266 Microcontroller Unit (MCU) from *Espressif Systems*. Every 10 ms, the MCU takes one package of data from the IMU (MPU-9250) consisting on six parameters (A_x, A_y, A_z, G_x, G_y, G_z). Also, through the 10-bit ADC, takes one sample of the analog input coming from the photoreceptor. Then, the microcontroller calculates the pitch, roll and yaw orientation of the drifter [20], packages all the data and sends it through Wi-Fi connection. Data is received on the boat router where a PC is continuously logging it and plotting in real time.

Finally, to validate the experimental results, a drifter has been simulated in OrcaFlex with the same parameters of TABLE I. Since the experiment has taken place in a controlled area, sea state could have been monitored during the experiment in order to replicate the same wave parameters. An Acoustic Doppler Current Profiler (ADCP) connected to an underwater observatory has provided the real wave height and period [21].

Figure 7 shows the drifter before the deployment at the sea.

Figure 7. Oceanic drifter with the KEH, the measuring electronics and the communication system on it.

IV. RESULTS

The experimental test was done on April 12th 2019 at the surroundings of OBSEA observatory {Lat.: 41.181954º, Long.: 1.752644º} in front of the coast of Vilanova i la Geltrú. As it is a monitored area, wave data could be obtained from the ADCP and it is shown at TABLE II.

TABLE II. Wave parameter during the experiment given by the ADCP.

Parameter	*Mean value*	*Max. Value*	*Units*
Wave height	0.49	0.73	m
Wave period	2.67	*6.47*	s
Wave direction	60	-	º(N)

Results are shown in two sections. Section A presents and analyzes the IMU data as well as the simulation results. At section B the performance of the KEH is discussed.

A. *Drifter motion*

Accelerometer IMU data has been analyzed. A_x, A_y and A_z linear acceleration obtained at the mass center are plotted at Figure 8, where 1 g is the gravity acceleration.

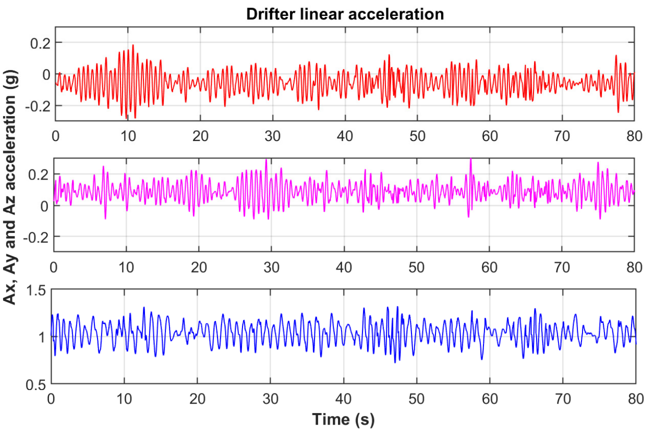

Figure 8. A_x, A_y and A_z linear accelerations from IMU sensor. In this section, red will be used for X axis, pink for Y axis and blue for Z axis.

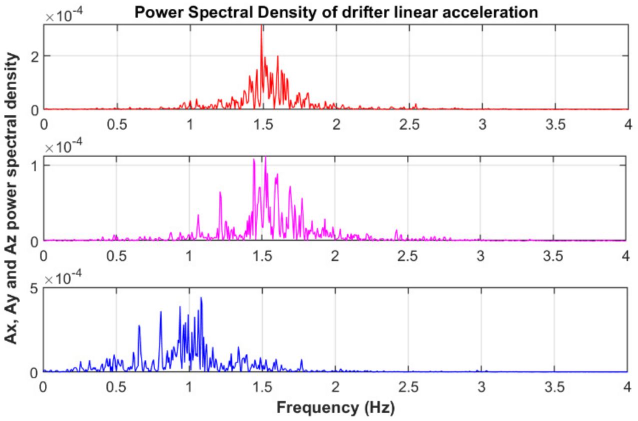

Figure 9. Power Spectrum of A_x, A_y and A_z linear accelerations from IMU sensor.

At the horizontal plane composed by X-Y axes, which are symmetrical, accelerations reach up to 0.2 g. The frequency domain of the signals has also been studied. The Fast Fourier Transform (FFT) has been applied to the whole signal (around 200 seconds) and it is shown at Figure 9. For horizontal axes, the natural frequency is found at 1.5 Hz. This movement represents the pendulum oscillation of the drifter due to the mass center displacement from the geometrical center (TABLE I). This frequency is not the waves frequency, which following ADCP information can be found at 0.4 Hz, but the natural frequency of the drifter when placed into a fluid.

Dynamics are different at the vertical axe, where acceleration moves between ± 0.2 g with an offset of 1 g due to gravity alignment. Its main frequency can be found at around 1 Hz, which is the rhythm of vibration at vertical axe. Vertical acceleration has also lower components as the one placed at 0.4 Hz originated by the wave oscillation.

Gyroscope IMU data has also been analyzed and G_x, G_y and G_z angular velocities plotted at Figure 10 in rad/s. The natural frequency of this movement has been calculated from the FFT and it is shown at Figure 11. Notice that this 1.5 Hz matches with the natural frequency of the linear acceleration at the horizontal plane that corresponds to the pendulum drifter motion.

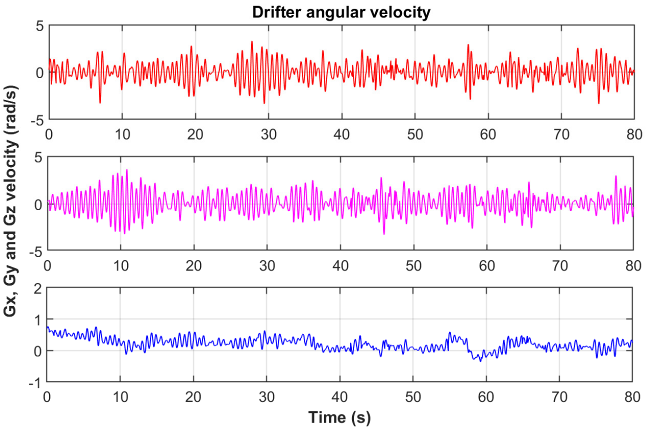

Figure 10. G_x, G_y and G_z angular velocities from the IMU sensor.

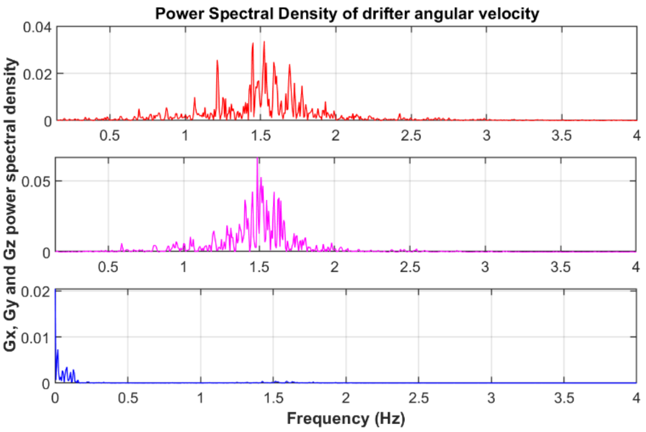

Figure 11. Power Spectrum of G_x, G_y and G_z angular velocities from IMU sensor.

Yaw motion has some low frequency component than generates its slow continuous rotation. This can be seen at G_z power spectrum plotted at Figure 11 where, apart from the 1.5

Hz pendulum motion, it contains some low frequency components. This can also be seen at Figure 10 where G_z contain positive offset that keeps yaw orientation rotating. This movement is supposedly caused by a small constructive error that causes a displacement of the center of mass of the vertical axis and, therefore, generates a torque among Z axe.

Pitch, Roll and Yaw orientation have been calculated from IMU data at NodeMCU and are plotted at Figure 12. Pitch and Roll oscillate with an amplitude of ±20º and Yaw from 180º to -180º repetitively at low motion.

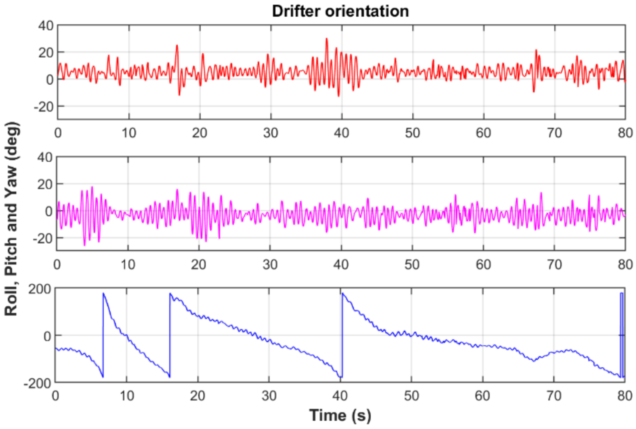

Figure 12. Roll, Pitch and Yaw orientation positions of the drifter during the experimental test calculated from IMU data.

To validate the obtained results, OrcaFlex simulation software has been used. A drifter as the one described in TABLE I has been modeled with a sphere composed by 24 stacked flat cylinders of different diameter (Figure 13). Mass center has been placed at 0.06 m of the sphere bottom. Sea state measured by ADCP and shown at TABLE II has been parametrized with JONSWAP model [22].

Figure 14 shows the power spectrum of linear acceleration obtained from simulation. Natural frequency of the pendulum motion at X-Y axis is found around 1.5 Hz. At vertical axe, the 1 Hz vibration can also be seen as well as the 0.4 Hz of sea elevation.

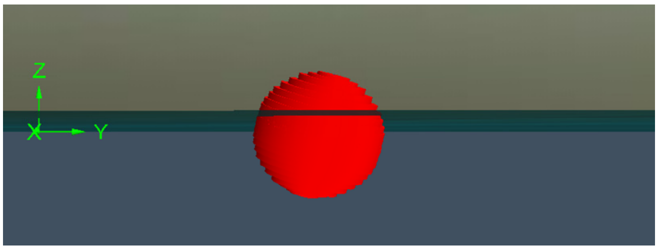

Figure 13. Oceanic WAVY drifter modeled by 24 stacked flat cylinders during the OrcaFlex simulation.

Figure 15 shows the power spectrum of the angular velocities obtained from the simulation. As expected, natural frequency of the drifter pendulum motion (1.5 Hz) can be found at X-Y axis. G_z power spectrum has no frequency component because, unlike the experimental case, the center of mass is placed on the vertical axis with no asymmetries.

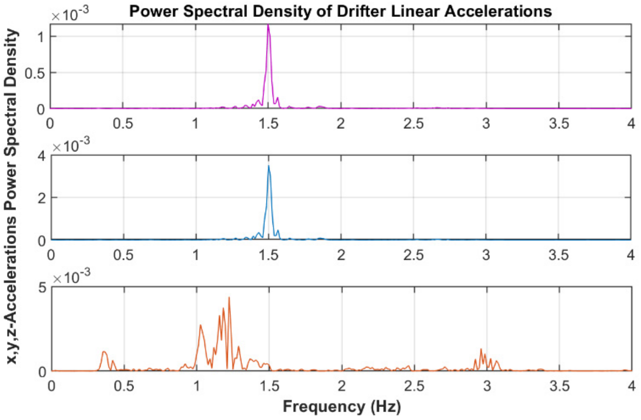

Figure 14. Power Spectrum of A_x, A_y and A_z linear acceleration from OrcaFlex Simulation tool. In this section, purple will be used for X axis, blue for Y axis and orange for Z axis

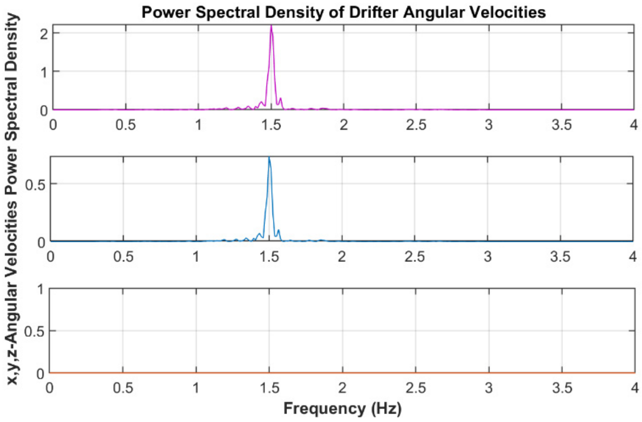

Figure 15. Power Spectrum of G_x, G_y and G_z angular velocities from OrcaFlex Simulation tool.

Later, different sea conditions have been simulated with the same drifter presented at TABLE I. Results show that the pendulum natural frequency of the drifter does not depend on the sea conditions but on its constructive parameters. As exposed at [23], the natural frequency of a body placed on a fluid depends on the fluid itself properties (density) and the spherical body design. Nevertheless, the magnitude of the accelerations and the potentially extractable power extraction do depend on the sea parameters such as wave frequency and height.

B. KEH rotation

Data obtained at the ADC coming from the photodiode has provided information about the KEH rotation. Figure 16 shows the digital signal of the ESP8266 ADC read after erasing the signal offset. Each pulse represents a complete rotation of the measured gear, which is supportive to the flywheel, being the high signal level the instant in which the emitter-receiver pair is aligned with the hole. The signal value grows with the infrared light intensity. At Figure 17, the ADC signal frequency domain has been plotted after applying the FFT and the main rotation frequency of the studied gear can be found between 1 and 2 Hz.

From the information provided by previous plots, the nearly continuous rotation of the device can be verified. The flywheel does not have a pulsating motion so it rotates continuously between 1 and 2 Hz.

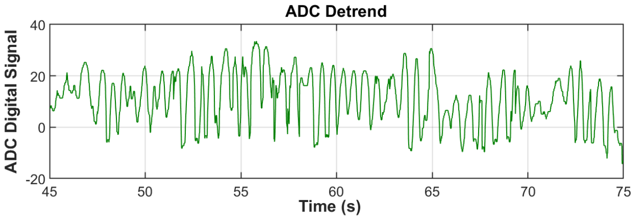

Figure 16. Analog read from the ESP8266 ADC showing the rotation behavior of the KEH.

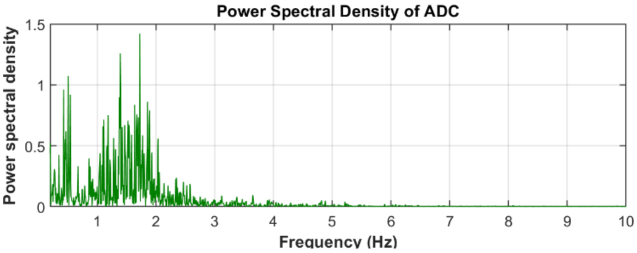

Figure 17. Power Spectrum of the Analog read from the ESP8266 ADC.

Given a transmission ratio of 15 between the studied gear and the micro generator, the micro generator rotation would be approximately 1400 rpm. Furthermore, according to the characterization done at previous works [16] (Figure 4), and assuming the PMU would achieve the MPPT, it can be concluded that about 2 mW could be generated. Finally, if the ADP5092 PMU also characterized in [16] is used, an efficiency of 80% would be obtained with this power input. That would mean 1.6 mW of useful power can be generated.

V. CONCLUSIONS

A designed KEH to be placed on a drifter has been tested at real sea conditions in a controlled area. The KEH consists on a pendulum system capable to transform the oscillations of the waves into rotation which would be converted into electrical energy thanks to a micro generator. A real drifter with the KEH has been deployed while an IMU sensor has provided information about its motion. The natural frequency of the pendulum motion of the drifter once deployed at the sea has been found at 1.5 Hz.

The same drifter has been modeled in OrcaFlex with the same experimental sea conditions read with an ADCP. Results show the natural frequency, similar to the one obtained at the experimental phase. Differences may be originated by the modeling of the spherical drifter. From the simulation of different sea states, it has been concluded that natural drifter pendulum motion does not depend on the wave parameters but on the drifter design.

The correct rotation of the KEH has also been monitored during the experiment thanks to a couple of infrared emitter-receiver. The rotation at the micro generator has been about 1400 rpm at nearly continuous operation. Also, its useful power output has been estimated at around 1.6 mW with the usage of the ADP5092 PMU.

For future woks, the frequency of resonance of the future KEH should be tuned at 1.5 Hz to maximize the power extraction. This is the natural frequency of the MELOA oceanic WAVY drifter. Also, to better understand the power generation, an in-situ power measurement system should be placed at the micro generator to know in real time the generated energy.

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