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# A NOTE ON USE OF A BOARDED PENDULUM FOR GENERATION OF ELECTRICITY

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***Abstract.*** *The nonlinear mathematical model of a pendulum attached to a platform subject to the ocean waves is presented in this paper. In order to use the waves to generate electrical energy, we transform the pendulum rotation movements into electrical energy by the introduction of an asynchronous electric motor of permanent magnet on the pendulum axis. The proposed mathematical model considers the vertical platform movements, and the pendulum rotation is subject to variation of the electric motor inertia movement. In order to optimize the power generation, different mass settings of the pendulum and electric motor are considered. The dynamic behavior of the system is shown through numerical simulations, as well as the efficiency of conversion of the pendulum movement in electricity.*

***Keywords:*** *Nonlinear dynamic, Pendulum, Energy Harvesting.*

## 1. INTRODUCTION

The demand for energy and the search for new energy sources has been growing in the recent years. In this sense the concept of renewable energy emerges as a new approach to obtaining clean energy without risks to the environment. Various devices have been developed, taking advantage of many different ways of exploiting the energy contained in the following processes: mechanical ones with kinetic, thermal or vibrational energy and electromagnetic with photovoltaic cells. As the kinetic energy is an energy source readily found in the environment, devices which convert kinetic energy into electrical energy have been widely studied (Iliuk *et al*., 2013).

According to Falnes (2007) waves can be used as a source of clean, renewable energy. In this context, Wiercigroch (2005) proposes generating energy from sea waves, considering the conversion of vertical oscillations into rotational movement, and uses the rotational movement to power an electric generator. Lin *et al*., 2013, proposed the use of a pendulum excited by sea waves to generate energy through a hydraulic system, a similar process is proposed by Tusset, *et al*. (2014).

Here we will use a similar strategy to that proposed by Wiercigroch (2005) and Lin *et al*. (2013), in which the movement of a pendulum on an offshore platform is harnessed to generate power, coupled the pendulum to a permanent magnet synchronous generator motor, taking advantage of the fluctuations of the waves to rotate the pendulum fast enough to generate electricity.

## 2. MATHEMATICAL MODELING OF THE DYNAMICAL SYSTEM

The representation of the pendulum coupled to an onboard generator model is shown in Fig. 1.

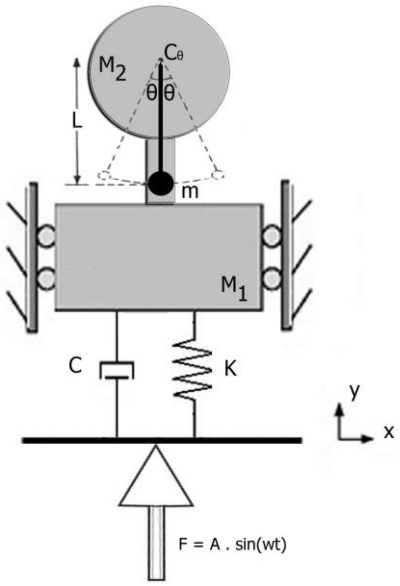



Figure 1. Pendulum excited by harmonic force

The model shown in Fig. 1 can be described as a pendulum coupled to a synchronous motor generator, fixed to a platform. The pendulum has mass $m$, with a rod of length $l$, $\theta$ is the angle of the pendulum. The generator has mass $M_2$, and platform mass $M_1$, and $M= M_1+M_2$, $k$ is associated with the fluid thrust reactions. The linear viscous damping of the fluid is represented by $c$, and the inertial torque of the generator is represented by $c_\theta$, $Y$ represents the vertical displacements of the platform and $F=A\sin(\omega t)$ the excitation source of the base. The dynamic equations of the system are obtained from the Lagrangian formulation (Kibble, 1970).

The kinetic energy $T$ and potential energy $V$ of the system are given by the Eq. (1) and Eq. (2) (Balthazar *et al.*, 2013):

$$T=\frac{1}{2}(M+m)\dot{Y}^2+\frac{1}{2}(M+m)\left(A^2\omega^2\cos^2(\omega t)\right)-(M+m)\dot{Y}\left(A\omega\cos(\omega t)\right)+\frac{1}{2}m\dot{\theta}^2 l^2+\left(m\dot{\theta}L\sin(\theta)\right)\left(\dot{Y}\omega\cos(\omega t)\right) \quad (1)$$

$$V=(Mg+mg)\left(Y-A\sin(\omega t)\right)+mgl\left(1-\cos(\theta)\right)+\frac{1}{2}k\left(Y^2+A^2\sin^2(\omega t)\right)-kY\left(A\sin(\omega t)\right) \quad (2)$$

From the system's energy, the Lagrange function is constructed, and the dynamic equations are presented as per the system in Eq. (3):

$$\begin{aligned}\ddot{Y}&=\frac{f_1 l-f_2\sin(\theta)}{(M+m)l-l\sin^2(\theta)}\\ \ddot{\theta}&=\frac{f_2(M+m)-f_1 ml\sin(\theta)}{(M+m)ml^2-ml^2\sin^2(\theta)}\end{aligned} \quad (3)$$

where $f_1$ and $f_2$ in Eq. (3) are presented by the Eq. (4) and Eq. (5):

$$f_1=-(M+m)\left(A\omega^2\sin(\omega t)-g\right)ml\dot{\theta}^2\cos(\theta)+k\left(A\sin(\omega t)-Y\right)-c\dot{Y} \quad (4)$$

$$f_2=-mlA\omega^2\sin(\omega t)\sin(\theta)-mgl\sin(\theta)-c_\theta l^2\dot{\theta} \quad (5)$$

Considering ( $x_1 = Y$ , $x_2 = \dot{Y}$ , $x_3 = \theta$ and $x_4 = \dot{\theta}$ ) we can represent the system of Eq. (3) as per Eq. (6):

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \frac{f_1 l - f_2 \sin(x_3)}{(M+m)l - l\sin^2(x_3)} \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= \frac{f_2(M+m) - f_1 m l \sin(x_3)}{(M+m)ml^2 - ml^2\sin^2(x_3)}
\end{aligned} \tag{6}$$

## 3. DYNAMIC BEHAVIOR OF THE SYSTEM

The dynamic behavior of the system was analyzed by means of numerical simulations, performed using the Runge-Kutta fourth order integrator with integration step h=0.01.

For numerical simulations, the parameters are: $M_1$ = 200 Kg, $g$ = 9.81 m/s², $k$ = 1800 Nm and $c$ = 80 Ns/m. The external excitation representing the movements of the sea were adapted from Carvalho (2010), considering the amplitude $A$ = 4.5 m and angular frequency $\omega$ = 1.2712 rad/s.

### 3.1 Dynamic behavior of the pendulum-platform system

Considering the system formed by the platform and the pendulum, coupled through a shaft with bearing, disregarding mass and internal friction in this study: $m$ = 4 kg and $l$ = 0.32 m. In Fig. 2 we can observe the system behavior.

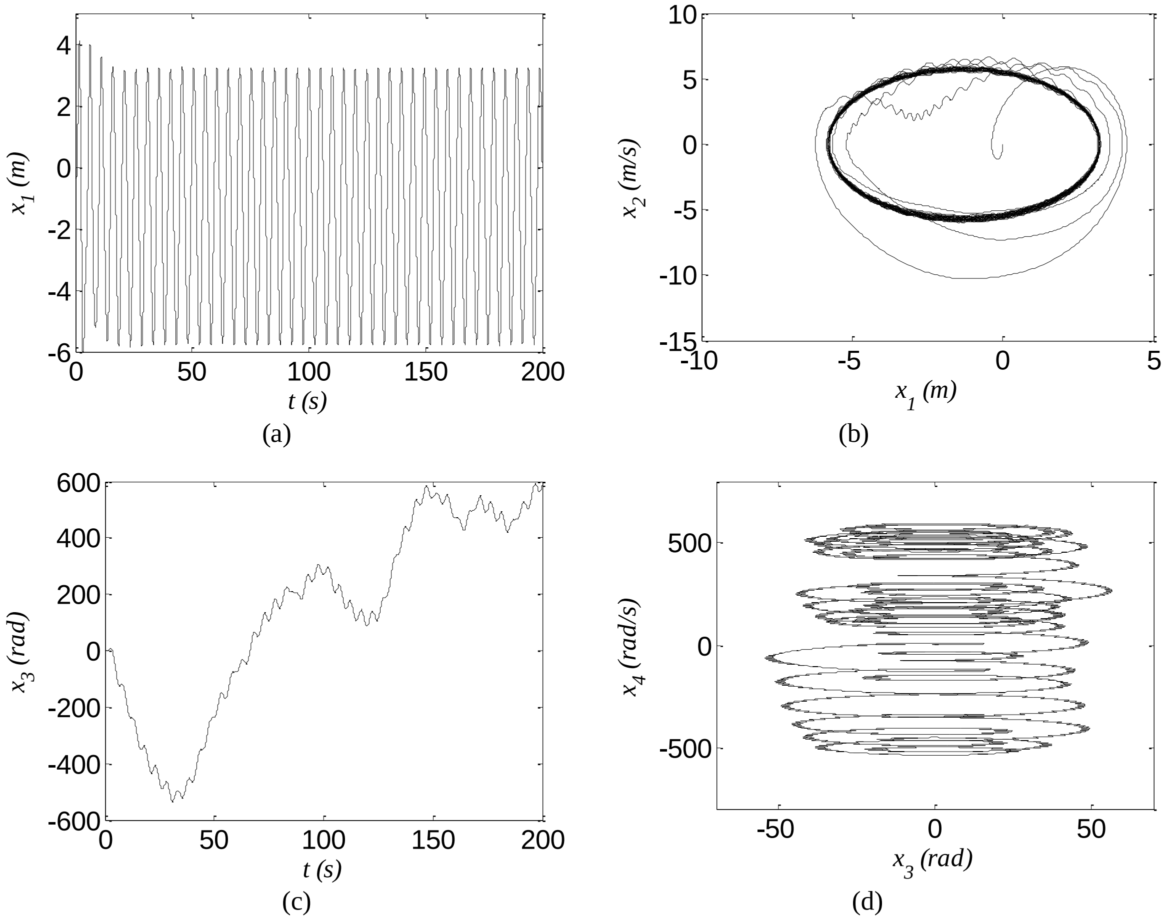



Figure 2. (a) Vertical displacement of the platform. (b) Phase diagram of the vertical displacement. (c) Angular displacement of the pendulum. (d) Phase diagram of the angular displacement.

As can be observed in Fig. 2c the platform oscillations (Fig. 2a) generate the rotational movement of the shaft pendulum, which can be used to generate electricity.

### 3.2 Dynamic behavior of the pendulum-generator-platform system

Considering now a system formed by the pendulum coupled to the axis of a synchronous permanent magnet generator motor, which in turn is fixed to the platform. Considering three generator motors with distinguished capacities: generator motor I: permanent magnet generator motor with 1000 W of generation capacity at 200 rpm, with mass $M_2$=28 Kg and inertial torque $c_\theta$=0.15 Nm. Generator motor II: permanent magnet generator motor with 1000 W of generation capacity at 180 rpm, with mass $M_2$=32 Kg and inertial torque $c_\theta$=0.3Nm. Generator motor III: permanent magnet generator motor with 500W generation capacity at 200 rpm, with mass $M_2$=20 Kg and inertial torque $c_\theta$ =0.1 Nm.

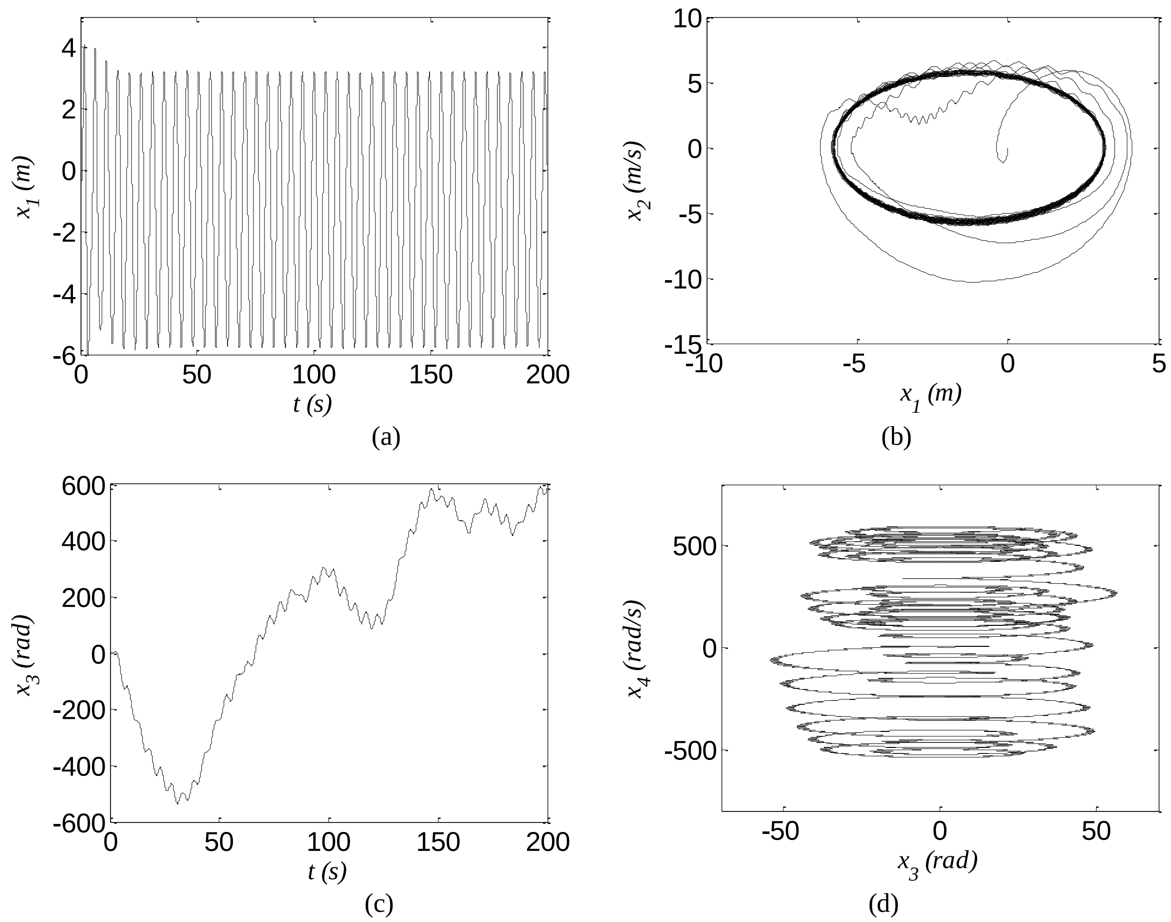
Whereas the generation of energy is proportional to rotation (rpm) we can define the following equation to estimate the energy for different velocities (rpm):

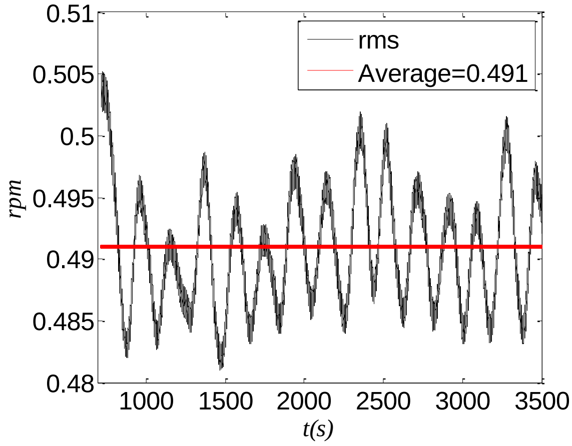
$$P_e = \frac{P_n R_v}{R_n} \tag{7}$$

where: $P_e$ is the estimated electrical power, $P_n$ is the nominal electrical power given by the manufacturer, $R_v$ is the variation of rotation in rpm and $R_n$ is the nominal rotation in rpm given by the manufacturer , $R_v$ may be calculated by the RMS through Eq. (8):

$$R_v = \sqrt{\frac{1}{n}\sum_{i=1}^{n} R_i^2} \tag{8}$$

In Fig. 3 we can observe the behavior of the system for generator motor I.



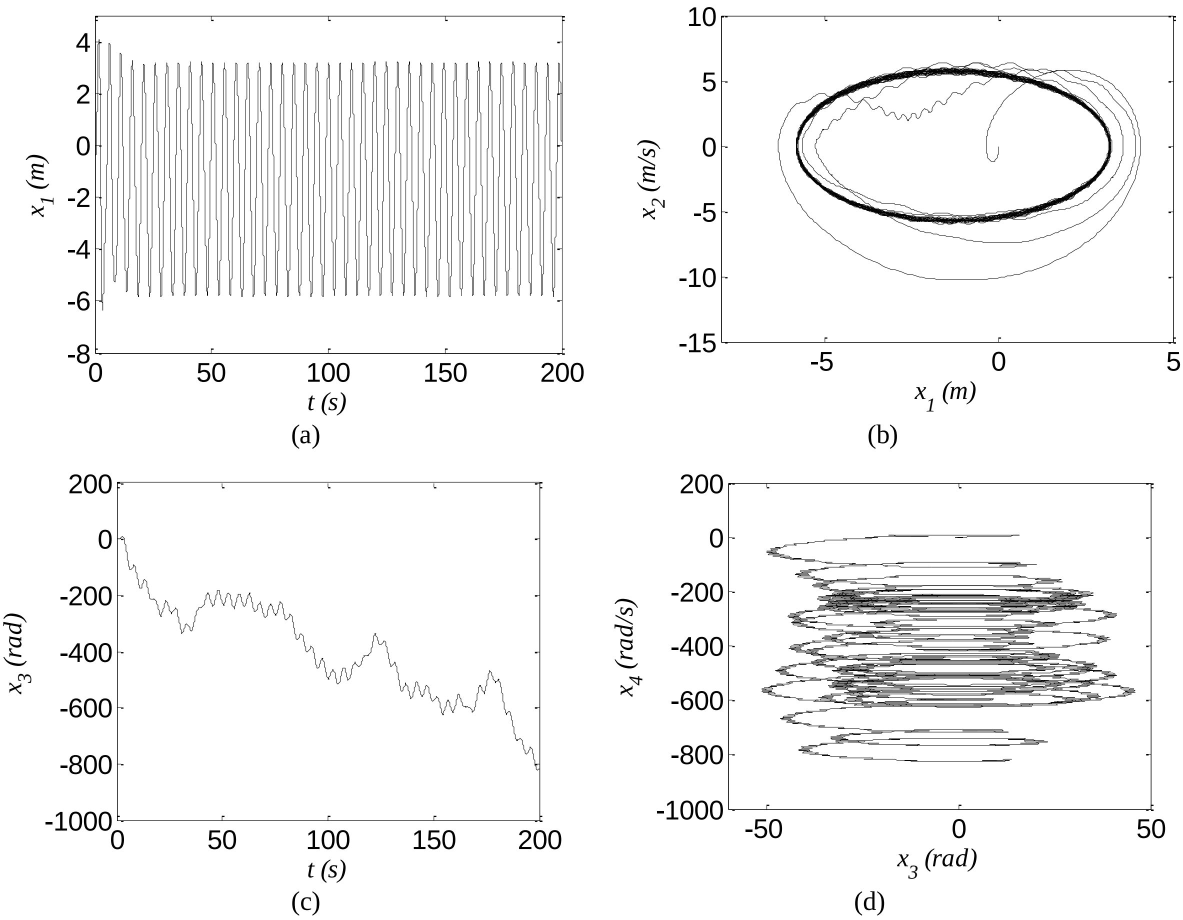


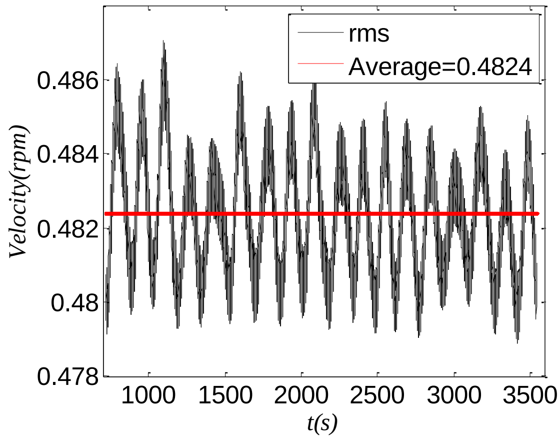

(e)

Figure 3. (a) Vertical displacement of the platform. (b) Phase diagram of the vertical displacement. (c) Angular displacement of the pendulum. (d) Phase diagram of the angular displacement. (e) Rotations (rpm) of the pendulum to a steady state

Considering the following parameters: $P_n = 1000$ W, $R_n = 200$ rpm and $R_v = 0.491$ rpm (Fig. 3e) obtained by Eq. (8), we can estimate the power by Eq. (7), with $P_e \approx 2.55$ W.

In Fig. 4 we can observe the behavior of the system for the motor II.



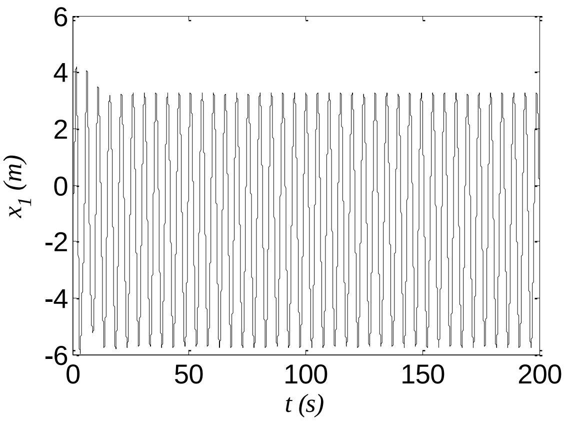



(e)

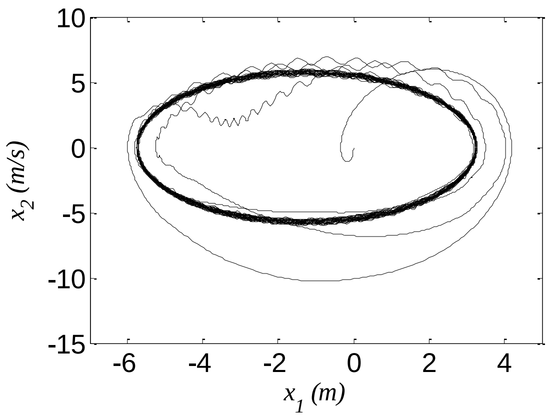
Figure 4. (a) Vertical displacement of the platform. (b) Phase diagram of the vertical displacement. (c) Angular displacement of the pendulum. (d) Phase diagram of the angular displacement. (e) Rotations (rpm) of the pendulum to a steady state

Now, we consider the following parameters: $P_n = 1000\,\text{W}$, $R_n = 180\,\text{rpm}$ and $R_v = 0.4824\,\text{rpm}$ (Fig. 4e) obtained by Eq. (8), we can estimate to power by Eq. (7), with $P_e \approx 2.68\,\text{W}$.

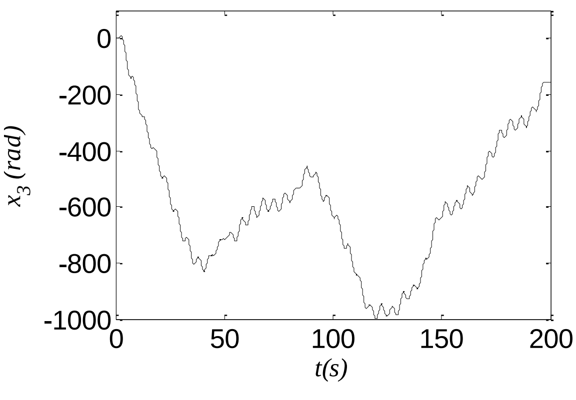
In Fig. 5 we can observe the behavior of the system for the motor III.



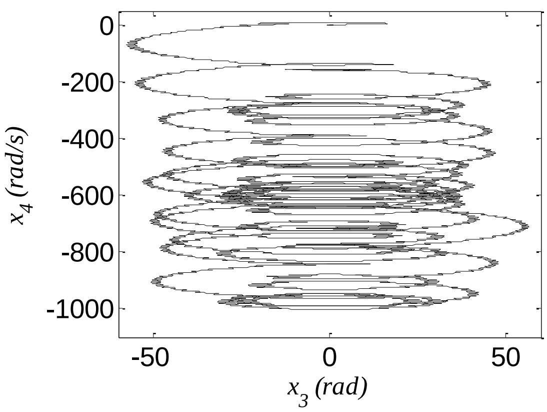

(a)



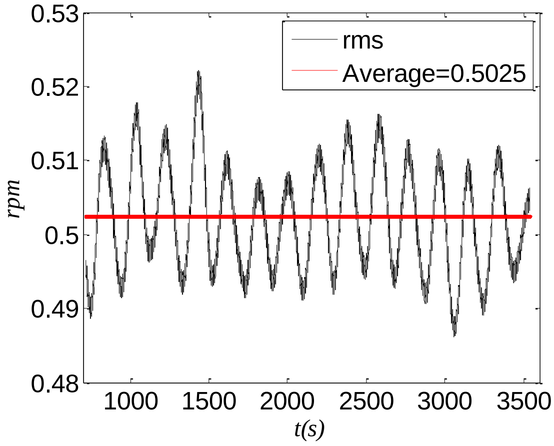

(b)




(c)




(d)




(e)

Figure 5. (a) Vertical displacement of the platform. (b) Phase diagram of the vertical displacement. (c) Angular displacement of the pendulum. (d) Phase diagram of the angular displacement. (e) Rotations (rpm) of the pendulum to a steady state

Considering the parameters $P_n = 500$ W, $R_n = 200$ rpm and $R_v = 0.5025$ rpm (Fig. 5e) obtained by Eq. (8), we can estimate the power by Eq. (7), with $P_e \approx 1.26$ W.

## 4. CONCLUSION

The results shown in figures 3, 4 and 5 show the possibility of exploitation of waves to generate electricity through a pendulum coupled to a synchronous generator of permanent magnet on a sea vessel. To demonstrate the feasibility of this study were considered three different types of motor generator synchronous permanent magnet available for such applications.

As can be seen, the results estimated to each case was below the nominal power of the generator motor which permits extension of the study to situations where either the frequency or the amplitude of the sea waves can be higher than those used in this study.

## 5. ACKNOWLEDGEMENTS

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