23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

On Energy harvesting from nonlinear Vibrations of a magnetic levitation system excited by an Electromechanical shaker

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Abstract. *The motivation of this work is to achieve a more effectiveness of energy harvesting devices exploiting nonlinear phenomena. In this way, this paper describes the design and analysis of a novel energy harvesting device that uses magnetic restoring forces to levitate an oscillating center magnet. The mathematical model for the energy harvesting device is derived and then examined for the case of eletro-mechanical base excitation. The magnetic levitation system has the form of a Duffing oscillator and, the nonlinear analysis is required to investigate the energy harvesting potential of this nonlinear system. We used some expressions related to coupling between the mechanical and electrical domains to describe the instantaneous power, besides we also developed an expression for the excitation frequency where the maximum power harvester is obtained.*

Keywords: *non linear dynamics, maglev, energy harvesting*

1. INTRODUCTION

The great demand in the use of new technologies has been growing exponentially over the past decades. According to ANEEL, the National Electric Energy Agency, in his Atlas of Electric Power (2009), all available energy sources on the planet, petroleum and its products stand out due to its wide use. However, due to its vast exploration due to the social and technological development, the planet is about to enter an energetic collapse. The oil reservation and natural gas will be exhausted in about 35 to 37 years, and coal in about 107 years, according to Shafiee and Topal (2008) and Shafiee and Topal (2009).

In view of such a problem, the study of new energy sources such as the concept of energy harvesting from vibration oscillatory systems, has increased in recent years and several jobs are found in the literature, such as Li et al. (2013); Litak et al. (2010); Marques et al (2014); Stephen, NG (2006a), Stephen, NG (2006b), Triplett and Quinn (2009) and Triplett et al. (2011), among others.

Most, if not all of these studies have focused on the power collected when the response behavior can be properly characterized as a linear oscillator with harmonic excitation. One conclusion from the literature on energy harvesters operating in the linear regime is that the maximum power is generated when the system is excited at resonance. This disadvantage puts a restriction on manufacturing processes that are used to build an energy collector.

A variety of methods have been used to convert environmental energy into electrical energy Roundy (2003). Among them stand out Energy harvester: capacitive / electrostatic, piezoelectric, and electromagnetic restrictive magneto.

This paper explores an alternative approach, considering the potential of energy harvesting when we consider the non-linearities of the system.This project proposes the analysis of a new energy harvesting device that uses magnetic forces to levitate a magnet oscillating center.

The goal is to use the non-linearity of the restoring forces to adjust the system provided maximum harvest of energy. The formulation of dynamical equations of the system shows the device can be model with the equation Duffing under excitation of an electrodynamic shaker. Investigating the frequency response for this non-linear system reveals the fact that the involvement non-linear response of the system could improve the harvested energy.

1.1 Energy harvest

The capture of energy is described as the ambient energy capture process and its conversion into electricity, and the interest as an energy source for future electronic devices conceptions and has grown substantially second (Priya & Inman, 2009).

In the environment of energy harvesting process, electrical energy is obtained by converting mechanical energy created by an ambient vibration source with a transducer, for example, a thin piezoceramic film (Iliuk, 2011).

Advances in technology are making portable electronic devices smaller and able to work with very low power consumption levels. These devices are most often fed by batteries that are finite energy sources.

Thus, there is the need to change or recharge these batteries periodically, a fact that can become a problem in some situations (Iliuk, 2011). An example that illustrates the situation described above is the use of conventional electrochemical batteries to power sensors installed in inaccessible places. When the battery power runs out, the sensors should be recovered in order to recharge the battery or even exchange them second (Cottone, 2007).

According (Fujitsu, 2010), in recent years the idea of use environmental energy in the form of light, heat, vibration, radio waves, etc., has become increasingly attractive, and many methods to produce electricity from the different types of energy sources have been developed.

According to (Iliuk, 2011), among the possible energy sources available in the environment, the kinetic energy is one of the energy sources that is most readily available. The principle of kinetic energy capture is movement or deformation of a structure contained within the energy capture device. This displacement or deformation can be converted into electrical energy by three methods: Piezoelectricity, electrostatic or magnetic induction as (Cottone, 2007).

The excitement of a magnetic mass through a coil generates energy limited by the amplitude and frequency of excitation through the damping coefficient (mechanical and electrical)(Stephen 2005). Also the efficiency of energy transfer is less than 50 % when losses occur both in the mechanical domain as the electric (Stephen 2006).

A device proposed by (Mann 2009) will be used as the basis of this paper. This device consists of a magnetic mass oscillating in a coil, causing a variation of the magnetic field within the coil and thereby inducing an electric current.

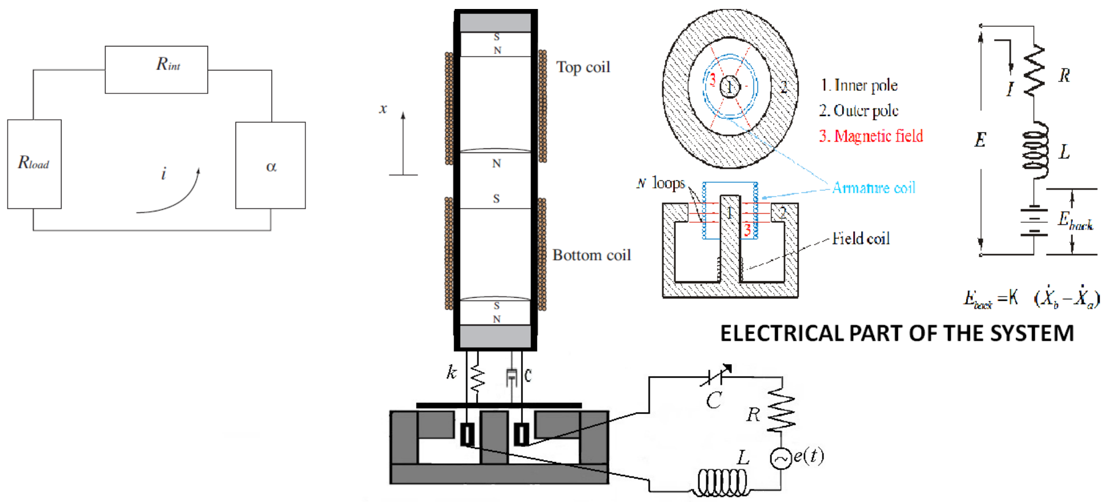


Figure 1. Energy harvesting device Mann (2009) modified

2. MATHEMATICAL MODEL

To be able to study the dynamics involved in a system using a mathematical model that had been adopted, there is the need to obtain the equations of motion. Thus, to determine the generalized coordinates and the inertial reference frame for each case.

It then calculates the position and the velocity of the bodies involved and as a result we obtain the energy equation and its derivatives, thus building the equations of motion using the methodology proposed by Lagrange in Analytical Mechanics.

Determine the generalized coordinates of this system, as follows:

For the oscillator we have:

$$\begin{cases} q_1 = 0 \Rightarrow \dot{q}_1 = 0 \\ q_2 = x \Rightarrow \dot{q}_2 = \dot{x} \end{cases} \tag{1}$$

For the electrical circuit, it is an analogy force voltage, based on the Law of Kirchhof Loops, with q the instantaneous electrical load, L inductance, R resistance, C capacitance and e the voltage source.

The terms L_s, R_s and C_s respectively represent the inductance, resistance and capacitance of the electro shaker.

Thus the energies **kinetic (T)**, **potential (V)** and **Rayleigh dissipation function (D)** are defined by:

$$T = \frac{1}{2}[m\dot{x}^2 + L_s\dot{q}^2] \tag{2}$$

$$V = mgx + \frac{1}{2}x^2(K_{mag_b} - K_{mag_t}) + S\dot{q}x) \tag{3}$$

$$D = \frac{1}{2}[c_m\dot{x}^2 + c_e\dot{x}^2 + R_s\dot{q}^2] \tag{4}$$

With $S = 2.\ Pi.N_s s.l.B_s$, where N_s is the number of shaker coil turns, l_s is the size of the coil, B_s is the average strength of the magnetic field of the shaker , c_m mechanical dumping, c_e electrical dumping and and K_{mag_b}, K_{mag_t} are respectively restoration forces of bottom and top magnetic.

From of system energies, we obtained the Lagrangian function, (L), which is defined by the difference between the energies kinetic (T) and potential (V).

$$L = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}L_s\dot{q}^2 - mgx - \frac{1}{2}x^2(K_{mag_b} - K_{mag_t}) - S\dot{q}x) \tag{5}$$

And system equations of motion are the derived of Lagrangian function in function of generalized coordinates and time.

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{x}}) - (\frac{\partial L}{\partial x}) + (\frac{\partial D}{\partial \dot{x}}) = 0 \tag{6}$$

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{q}}) - (\frac{\partial L}{\partial q}) + (\frac{\partial D}{\partial \dot{q}}) = e.cos(\Omega.t) \tag{7}$$

Thus the system of equations for the oscillating system is given by:

$$\begin{cases} m\ddot{x} + mg + x(K_{mag_b} - K_{mag_t}) + S\dot{q} + c_m\dot{x} + c_e\dot{x} = 0 \\ L_s\ddot{q} - S\dot{x} + R_s\dot{q} = ecos(\Omega t) \end{cases} \tag{8}$$

2.1 Magnetic force definition (K_{mag})

In accordance with experiment conducted by man Mann (2009) the magnetic force can be expressed as a power series.

$$F(x) = F_b - F_t = \sum_{n=0}^{3} \alpha_n (x+d)^n - \sum_{n=0}^{3} \alpha_n (d-x)^n \tag{9}$$

Where F_b is the force of the lower magnet, F_t is the force of the upper magnet and d is the spacing between the magnets.

Thus:

$$F(x) = (2\alpha_1 + 4d\alpha_2 + 6d^2\alpha_3)x + 2\alpha_3 x^3 = kx + k_3x^3 \tag{10}$$

Therefore, it is possible to rewrite the system of equations 8 as follows

$$\begin{cases} m\ddot{x} + mg + kx + k_3x^3 + S\dot{q} + (c_m + c_e)\dot{x} = 0 \\ m\ddot{q} - S\dot{x} + R_s\dot{q} = ecos(\Omega t) \end{cases} \tag{11}$$

2.2 Equations for energy harvesting model

The circuit shown below, is the energy harvesting circuit through electromagnetic forces induced by the magnetic oscillator. The equation for the electric circuit of energy harvesting is obtained by applying the Kirchoff's law for electrical circuits.

$$i.(R_{load} + R_{int}) - \alpha\dot{x} = 0 \qquad (12)$$

Where $i = \frac{dq}{dt}$ is the electric current, R_{load} and R_{int} are the external and internal resistances respectively and α is the electromechanical coupling term defined for $\alpha = NLB$ with N is the number of coil turns, l the size of the coil and B is the average magnetic field strength.

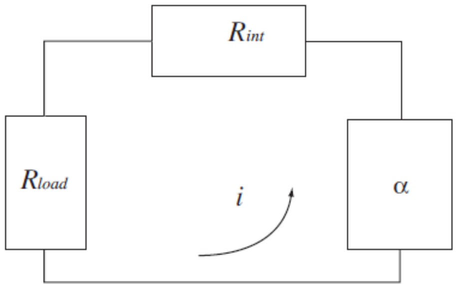


Figure 2. Diagram of energy harvesting circuit

According to the Lenz's Law, the electric damping arises from the introduction of the coil to convert mechanical energy into electricity. Thus, the equation 12, it follows that:

$$i = \frac{\alpha}{R_{load} + R_{int}}\dot{x} \qquad (13)$$

Therefore,

$$c_e = \frac{\alpha^2}{R_{load} + R_{int}} \Rightarrow i = \frac{c_e}{\alpha}.\dot{x} \Rightarrow \alpha.i = c_e.\dot{x} \qquad (14)$$

Thus the term c_e and $\dot{x}$ was conveniently introduced in the model.

2.3 Simplifying the equations

$$\begin{cases} \ddot{x} + g + \omega_1^2 x + \omega_3^4 x^3 + \delta_1\dot{q} + (C_m + C_e)\dot{x} = 0 \\ \ddot{q} - \delta_2\dot{x} + \omega_2^2\dot{q} = E_0 cos(\Omega.t) \end{cases} \qquad (15)$$

where

$$\omega_1 = \sqrt{\frac{k}{m}}, \quad \omega_2 = \sqrt{\frac{R_s}{L_s}}, \quad \omega_3 = \sqrt[4]{\frac{k_3}{m}}, \quad \delta_1 = \frac{S}{m}, \quad \delta_2 = \frac{S}{L_s},$$
$$E_0 = \frac{F_0}{L_s}, \quad C_m = \frac{c_m}{m}, \quad C_e = \frac{c_e}{m}, \quad e = F_0, \quad C = \frac{1}{C_s}$$

Do

$$x = X_1, \quad \dot{x} = X_2, \quad q = X_3, \quad \dot{q} = X_4$$

The system in state space can be written as follows:

$$\begin{cases} \dot{X}_1 = x_2 \\ \dot{X}_2 = -\omega_1^2 X_1 - \omega_3^4 X_1^3 - (C_m + C_e)X_2 - \delta_1 X_4 - g \\ \dot{X}_3 = x_4 \\ \dot{X}_4 = \delta_2 X_2 - \omega_2^2 X_4 + e.cos(\Omega.t) \end{cases} \qquad (16)$$

In matrix form we have:

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -{\omega_1}^2 & -C_m - C_e & 0 & -\delta_1 \\ 0 & 0 & 1 & 0 \\ 0 & \delta_2 & 0 & -{\omega_2}^2 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ {\omega_3}^4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} {X_1}^3 \\ {X_2}^3 \\ {X_3}^3 \\ {X_4}^3 \end{bmatrix} + \begin{bmatrix} 0 \\ -g \\ 0 \\ E_0 \cos{(\Omega\, t)} \end{bmatrix} \qquad (17)$$

Substituting $I = \dot{q}$ we have:

$$\begin{cases} \ddot{x} + g + \omega_1^2 x + \omega_3^4 x^3 + \delta_1 I + (C_m + C_e)\dot{x} = 0 \\ \dot{I} + \omega_2^2 I - \delta_2 \dot{x} = E_0 cos(\omega t) \end{cases} \tag{18}$$

Do

$$x = X_1, \quad \dot{x} = X_2, \quad I = X_3$$

The system in state space can be written as follows:

$$\begin{cases} \dot{X}_1 = x_2 \\ \dot{X}_2 = -\omega_1^2 X_1 - \omega_3^4 X_1^3 - (C_m + C_e)X_2 - \delta_1 X_3 - g \\ \dot{X}_3 = \delta_2 X_2 - \omega_2^2 X_3 + E_0 cos(\omega t) \end{cases} \tag{19}$$

In matrix form we have:

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -{\omega_1}^2 & -C_m - C_e & -\delta_1 \\ 0 & \delta_2 & -{\omega_2}^2 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ {\omega_3}^4 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} {X_1}^3 \\ {X_2}^3 \\ {X_3}^3 \end{bmatrix} + \begin{bmatrix} 0 \\ -g \\ E_0 \cos(\Omega\, t) \end{bmatrix} \tag{20}$$

3. Numerical simulation

3.1 eigenvalues analyses

Analysing the linear part of the system is possible to observe that the only point of static equilibrium is the point $[X_1 \;\; X_2 \;\; X_3] = [0 \;\; 0 \;\; 0]$.

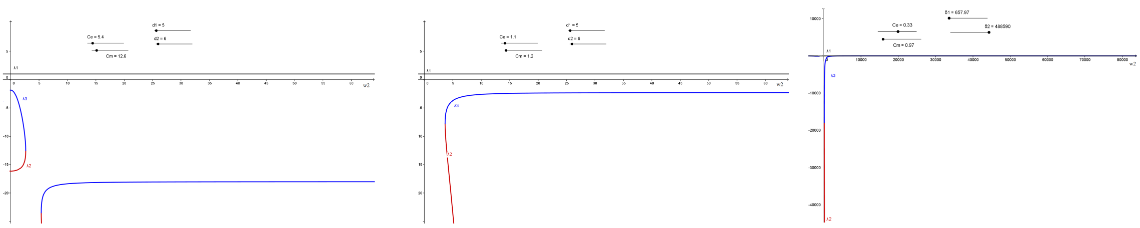
$$\begin{vmatrix} 1-\lambda & 0 & 0 \\ -{\omega_1}^2 & -C_m - C_e - \lambda & -\delta_1 \\ 0 & \delta_2 & -{\omega_2}^2 - \lambda \end{vmatrix} = 0$$

Thus, the characteristic polynomial the linear system is defined by:

$$\lambda^3 - \left(-{\omega_2}^2 + 1 - C_m - C_e\right)\lambda^2 - \left(-\delta_2\delta_1 + {\omega_2}^2 - {\omega_2}^2 C_m - {\omega_2}^2 C_e + C_m + C_e\right)\lambda - \delta_2\delta_1 - {\omega_2}^2 C_m - {\omega_2}^2 C_e = 0$$

Whose roots are:

$$\begin{bmatrix} 1 \\ -\frac{1}{2}\, C_e - \frac{1}{2}\, {\omega_2}^2 - \frac{1}{2}\, C_m + \frac{1}{2}\sqrt{{C_e}^2 - 2\, {\omega_2}^2 C_e + 2\, C_e C_m + {\omega_2}^4 - 2\, {\omega_2}^2 C_m + {C_m}^2 - 4\, \delta_2 \delta_1} \\ -\frac{1}{2}\, C_e - \frac{1}{2}\, {\omega_2}^2 - \frac{1}{2}\, C_m - \frac{1}{2}\sqrt{{C_e}^2 - 2\, {\omega_2}^2 C_e + 2\, C_e C_m + {\omega_2}^4 - 2\, {\omega_2}^2 C_m + {C_m}^2 - 4\, \delta_2 \delta_1} \end{bmatrix}$$



(a) (b) (c)

Figure 3. Eigenvalues (a) $\delta_1 = 5$, $\delta_2 = 6$, $C_m = 12.6$, $C_e = 5.4$, (b) $\delta_1 = 5$, $\delta_2 = 6$, $C_m = 1.2$, $C_e = 1.1$ and (c) $\delta_1 = 657.97$, $\delta_2 = 488590$, $C_m = 0.9744$, $C_e = 0.3256$

Analysing dependence parameters of eigenvalues we have $\lambda_1\lambda_2 > 0$ but $\lambda_1 < 0$ and $\lambda_2 < 0$ fig 3 except for a little interval of external frequency of shaker (ω_2) where the eigenvalues assumes complex values.

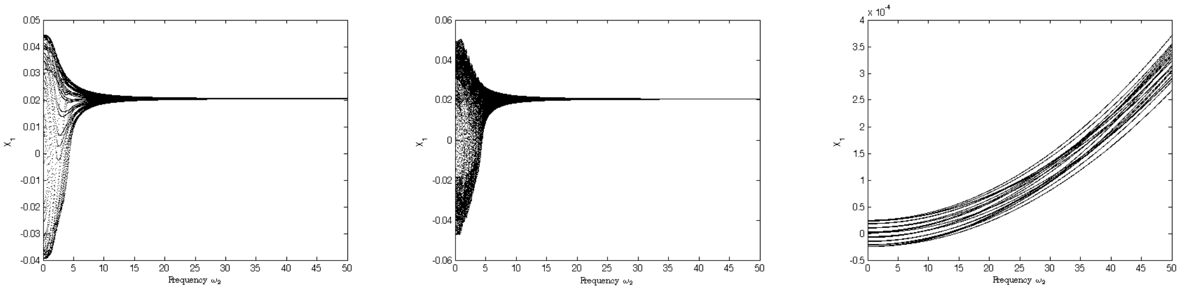
For better comprehension of the system we need to analyse a dynamical behavior for each value of ω_2

3.2 dynamical behaviour

The dynamical behavior of the system is analyse through numerical simulations using a 4th order Runge Kutta solver (ODE45), and the algorithms were made in Matlab®. The analyses occurred through signal of eigenvalues, Phase-Plane, Time domain response of the system and Bifurcation Diagrams.

As can be seen in Fig 4a, when the frequency of shaker evolve from $0.1rad/s$ to about $15rad/s$ the system maintains a multi periodic behavior. On the other hand, the system has a periodic behavior for ω_2 up to $15rad/s$.

In Fig 4b, has the same behavior of Fig 4a, but in Fig 4c the system keeps a multi periodic behavior from the beginning to the end of the analysis.



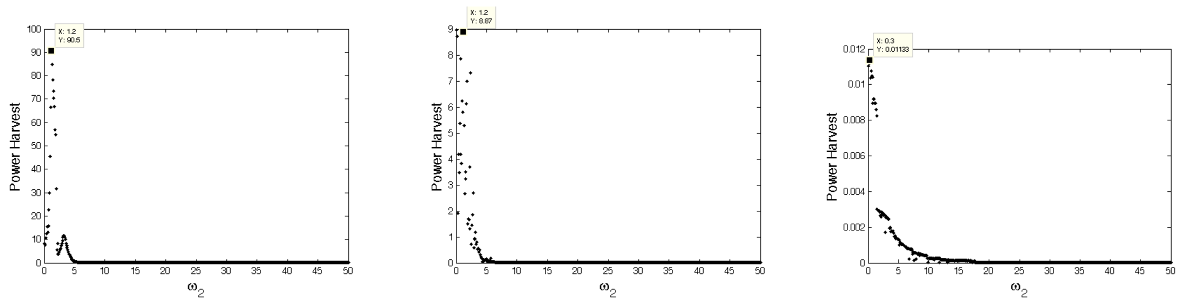
(a) (b) (c)

Figure 4. Bifurcation Diagrams (a) $\delta_1 = 5$, $\delta_2 = 6$, $C_m = 12.6$, $C_e = 5.4$, (b) $\delta_1 = 5$, $\delta_2 = 6$, $C_m = 1.2$, $C_e = 1.1$ and (c) $\delta_1 = 657.97$, $\delta_2 = 488590$, $C_m = 0.9744$, $C_e = 0.3256$

3.3 Proposed design for energy harvesting

According to equation 14 $i = \frac{c_e}{\alpha}.\dot{x}$. So we cam write the power harvesting as

$$P(\omega_2) = i^2 R_{load} = (\frac{\alpha}{R_{load} + R_{int}}\dot{x})^2 R_{load} \Rightarrow P(\omega_2) = (\frac{C_e}{\alpha}\dot{x})^2 R_{load} \tag{21}$$

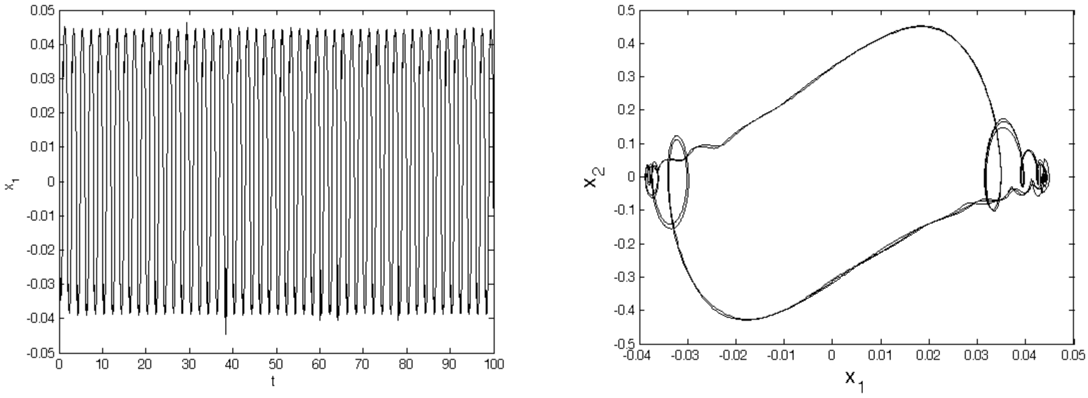


(a) (b) (c)

Figure 5. Power Harvesting (a) $\delta_1 = 5$, $\delta_2 = 6$, $C_m = 12.6$, $C_e = 5.4$, (b) $\delta_1 = 5$, $\delta_2 = 6$, $C_m = 1.2$, $C_e = 1.1$ and (c) $\delta_1 = 657.97$, $\delta_2 = 488590$, $C_m = 0.9744$, $C_e = 0.3256$

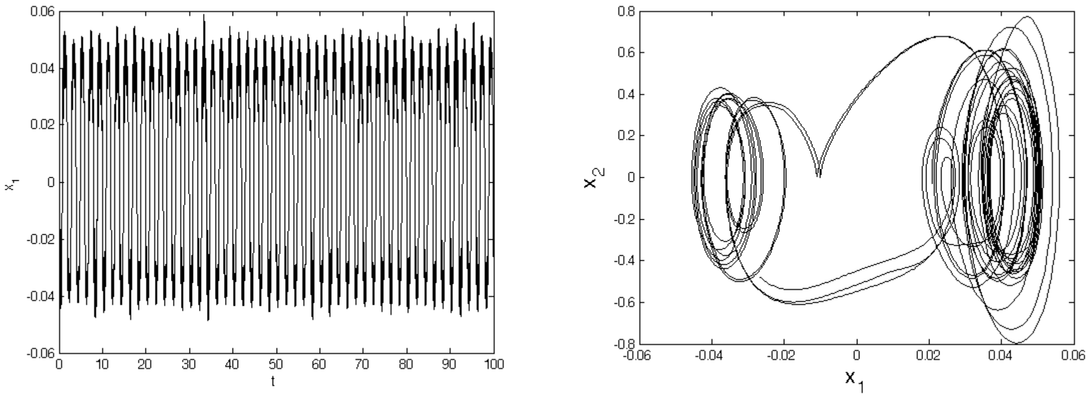
In Fig 5 we can observe the variation of the objective function 21 for a variation of the pω_2 in the range $0.1 \leq \omega_2 \leq 50$. We cam observe that the maximum power harvest occurs on $\omega_2 = 1.2$ (Fig 5a) harvesting $8.87W$; $\omega_2 = 1.2$ (Fig 5b) harvesting $90.5W$ and $\omega_2 = 0.3$ (Fig 5c) harvesting about $0.01W$.

According to Figures 6 7 and 8, we can observe that the maximum energy harvesting occurs when the system has a multi periodic behavior and setting de parameter as Fig 6 we have a better energy harvest of the tree set of parameters.



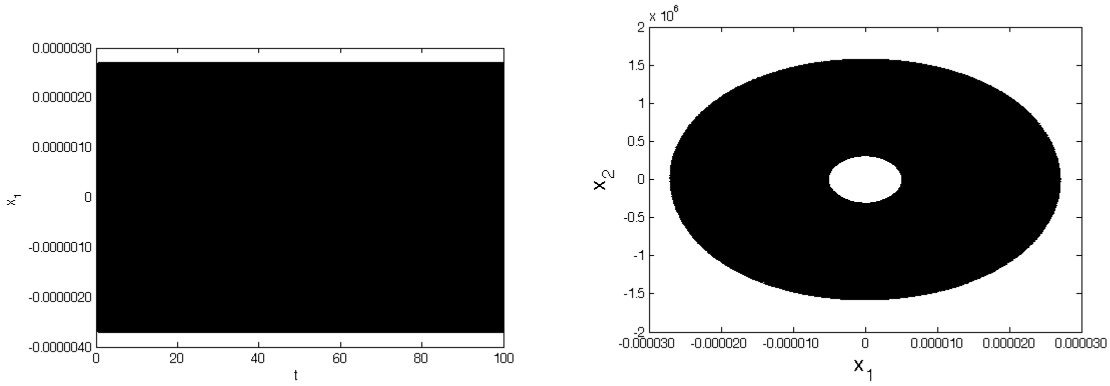
(a) (b)

Figure 6. Dynamic behavior os the system on maximal power harvesting $\delta_1 = 5$, $\delta_2 = 6$, $C_m = 12.6$, $C_e = 5.4$ and $\omega_2 = 1.2$ (a) Time displacement X_1 e (b) Phase plane



(a) (b)

Figure 7. Dynamic behavior os the system on maximal power harvesting $\delta_1 = 5$, $\delta_2 = 6$, $C_m = 1.2$, $C_e = 1.1$ and $\omega_2 = 1.2$ (a) Time displacement X_1 e (b) Phase plane



(a) (b)

Figure 8. Dynamic behavior os the system on maximal power harvesting $\delta_1 = 657.97$, $\delta_2 = 488590$, $C_m = 0.9744$, $C_e = 0.3256$ and $\omega_2 = 0.3$ (a) Time displacement X_1 e (b) Phase plane

4. CONCLUSIONS

The results of the dynamic analysis show that the system has multi periodic and periodic behavior according to value of frequency of excitation source (EDS) and a better energy harvesting occurs on multi periodic regions.

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6. RESPONSIBILITY NOTICE