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DYNAMICS ANALYSIS OF THE PORTAL FRAME MODEL WITH NON-IDEAL DRIVE AS AN ENERGY HARVESTER

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Abstract: Several researchers have been trying to find the best model for generating electrical energy from environmental vibration, that is the best solution for many applications nowadays. Then, in this paper, a model of energy harvesting with a non-ideal force of excitation and nonlinear piezoelectric coupling is proposed. The non-ideal force is a DC motor with an unbalanced mass. And the analysis of the system is performed by means of numerical simulation, that compared an influence of rotation of DC motor with the power harvesting, where this influence is verified for three cases of vibration, one in the region of pre-resonance, other in region of post-resonance and a last in the region of resonance. Hence, it was possible to present the consequence of the Sommerfeld effect in the power harvested and it is shown that this phenomenon is not good to energy harvesting. And to ascertain this effect, it was compared the displacement of structure and angular velocity of DC motor for these cases. Furthermore, the system was analyzed with Wavelet Transform, that allowed to verify when the system have more energy, with more precision.

Keywords: Energy harvesting, Piezoelectric, Sommerfeld effect, Wavelet Transform.

1. INTRODUCTION

Currently, with the development of technology, there are being produced several mobile electronic devices that operate with consumption ever lower, for example devices that use batteries. Then, the necessity to develop ways for its supply and become independent of batteries has been calling attention of many researchers. Some works present the study of energy harvesting, that harvest energy from the environment and convert it in electricity, as (Erturk *et al.*, 2009), (Shu and Lien, 2006) and (Erturk and Inman, 2008).

There are lots of different kinds of energy harvesters and in Wei and Jing (2017) a review about these devices is presented. The harvesters can be electromagnetic, electrostatic and piezoelectric, being the latter the most often used. The piezoelectric materials are those that have characteristic that through a mechanical stimulus, it generates an electrical charge, provide the electricity. In addition Lumentut and Howard (2013), Wang and Meng (2013) and Chen *et al.* (2013) some typical energy harvesting applications using piezoelectric are presented.

As a way of analyzing this energy harvesting, the researchers ought to study which model of system they will applied. And the portal frame model is often used to analyze the behavior of many mechanical systems that exhibit non-linearities and loss of stability when subjected to dynamic loads. For example, in Iliuk *et al.* (2013) it was proposed a model using a passive control technique with a simple pendulum, to tune the vibration of the portal frame to improve the power harvested. Besides, many researchers have studied to find the best configuration to harvest energy and to optimize the power output in other types of structure. As in Wu *et al.* (2013) where the energy harvested in cut-out configuration beam is studied and Roundy and Wriht (2004), Roundy *et al.* (2003) a cantilever beam with a mass placed on its free end are designed.

In this paper, the model of the energy harvested across a two degree of freedom portal frame excited by a non-ideal DC motor with an unbalanced mass is proposed. The piezoelectric has been modeled to have a non-linear coupling. Also, it was studied the influence of some parameters in the power output for three cases of vibration, one in the region of pre-resonance, other in region of post-resonance and a last in the region of resonance.

Beyond that, it was analyzed the influence of the Sommerfeld effect in the system, through the variation of the control parameter, that will control the voltage applied to the motor. An useful way to check this effect is to see the displacement

of structure and angular velocity of DC motor, that when the system oscillate with the frequency higher than natural frequency, the amplitude tend to decrease and angular frequency to increase.

For concluding, it was used a tool that decomposes the signal at different scale, with different resolution, through one function, that it's known as Wavelet Transform (Santoso *et al.*, 1996). In which there are far-reaching applications in studies of physics, mathematics, computing and engineering. In according to Addipson (2017a) there are a lot of examples of applications and the assessment of Wavelet Transform. It was used a Continuous Wavelet Transform to exploring the response in time and frequency domain of this mechanical system with more precision than Fourier Transform, because it can be applied to non-stationary signals and to detect discontinuities in a signal (Mallat, 2008). Hence, it was possible to clarify when the system will have more energy and this analysis was done in form of scalogram.

2. MATHEMATICAL BACKGROUND FORMULATIONS

In this paper a portal frame with layers of piezoelectric element (piezoceramic) is proposed and a non-ideal excitation is attached, that consists an electric DC motor with an unbalanced mass as shown in Fig. 1.

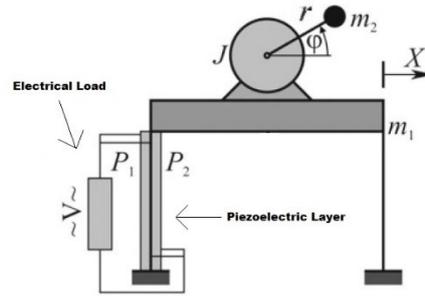


Figure 1: Portal Frame with DC motor and Piezoelectric applied.

Furthermore, the layers of piezoelectric applied in just one column of the portal frame and on both of surface, that the configuration is bi-morph (Anton and Sodano, 2007), as it is seen in the Fig. 1 (P_1 and P_2 represents the piezoelectric film).

The columns of portal frame structure are a duffing type (Tusset *et al.*, 2012), that have a cubic nonlinearity, in other words, the stiffness (K) is equal of $-k_1 \cdot X - k_2 \cdot X^3$. The non-ideal excitation consists in a resistive torque applied to the motor, in according to (Balthazar *et al.*, 2003) and (Iliuk *et al.*, 2012), is an exponential function, that represent the curve of torque versus velocity of DC motor. This function is $L(\dot{\varphi}) - H(\dot{\varphi}) = V_1 \cdot e^{-V_2 \cdot \dot{\varphi}}$, where the V_1 is a voltage applied on the DC motor and V_2 is a constant for each model of DC motor.

Besides, there is a coupled circuit in the system and in according to Triplett and Quinn (2009), the term $\frac{d(X)}{C}q$ represents piezoelectric coupling to the mechanical component. Where the electrical charge is given by q and $d(X)$ is a strain-dependent coupling coefficient.

All the structure (portal frame and DC motor) have two degree-of-freedom given with two coordinates X and φ . That X is the displacement of portal frame and φ is the rotation angle of DC motor. The equation of motions is obtained through *Lagrange's equation*. And in according to Iliuk *et al.* (2012) the equation is:

$$\begin{aligned} (m_1 + m_2)\ddot{X} + c\dot{X} + k_1X + k_1X^3 &= m_2 r (\ddot{\varphi} \cos \varphi - \dot{\varphi}^2 \sin \varphi) + \frac{d(X)}{C}q \\ (J + m_2 r^2)\ddot{\varphi} &= m_2 r \dot{X} \cos \varphi + V_1 e^{-V_2 \dot{\varphi}} \\ R\dot{q} - \frac{d(X)}{C}X + \frac{q}{C} &= 0 \end{aligned} \quad (1)$$

Where c is a mechanical damping, C is a piezoelectric capacitance, R is piezoelectric resistance and q is an electrical charge. The third equation is the coupled circuit (Triplett and Quinn, 2009).

But in this paper considerer the following non-dimensional parameters, on may refer to Iliuk *et al.* (2012) for more details. And based on the results of Crawley and Anderson (1990) and in according to Triplett and Quinn (2009) the dimensional piezoelectric coupling coefficient is $d(X) = \theta (1 + \Theta |X|)$, where this equation has a piezoelectric coefficient by a linear part (θ) and a non-linear part (Θ). And after the all non-dimensionalities we reduce the equation of motion to:

$$\begin{aligned} x'' + \varepsilon \alpha x' + \beta x + \varepsilon \beta_1 x^3 - \varepsilon \theta (1 + \Theta |x|)\nu &= \varepsilon \delta_1 \varphi'' \cos \varphi - \varepsilon \delta_2 \varphi' \cos \varphi \\ \varphi'' &= \varepsilon \mu_1 e^{-\mu_2 \dot{\varphi}} + \varepsilon \gamma x'' \cos \varphi \\ \rho \nu' - \theta (1 + \Theta |x|)x + \nu &= 0 \end{aligned} \quad (2)$$

Moreover, knowing that the voltage defined as $V = -R \dot{q}$ and the power harvested from the mechanical system is $\frac{V^2}{R}$, and conform Anton and Sodano (2007) and Triplett and Quinn (2009) the non-dimensional power harvested is:

$$P = \rho v'^2 \tag{3}$$

To conclude the study, in this work, it was used method of signal processing known as the Continuous Wavelet Transform (CTW). And the CWT of signal F , at time u and scale s , is defined as:

$$WF(u, s) = \int_{-\infty}^{\infty} F(t)\psi_{u,s}^*(t)dt \tag{4}$$

Where $\psi_{(u,s)}^*$ is:

$$\psi_{(u,s)}^* = \frac{1}{\sqrt{s}}\psi\left(\frac{t-u}{s}\right) \tag{5}$$

Thus, in according to Eq. 6 it is possible to obtain the scalogram of F , denoted by ς as Benítez *et al.* (2010). :

$$\varsigma := ||WF(u, s)|| = \sqrt{\int_{-\infty}^{\infty} |F(t)\psi_{u,s}^*(t)|^2 du} \tag{6}$$

3. RESULTS AND DISCUSSIONS

To perform the numerical simulations, the parameters considered for dynamics system are listed in Tab. 1.

Table 1: **Parameter used to simulation**

Parameter	Value
m_1 [kg]	0,416
m_2 [kg]	0,659
r [m]	0,015
ε	0,0016
α	0,0087
γ	0,55
ρ	0,54
δ_1	0,0016
δ_2	5,74
β	1
β_1	2,5
μ_2	1,5

And the value of linear piezoelectric coupling (θ) is equal 0.5 and nonlinear piezoelectric coupling (Θ) is equal 1.5. According to Iliuk *et al.* (2012) these values of piezoelectric coupling are the best, because it increases the maximum power harvested and keep on stable behavior in the region of pre-resonance and in the region of resonance.

3.1 Curve of Resonance

For the analysis of the model, it is necessary to relate the value of the control parameter (μ_1) with the amplitude of vibration. And when this is done, one is able to notice what control parameter will affect the resonance. Therefore, in the Fig. 2 shows this curve.

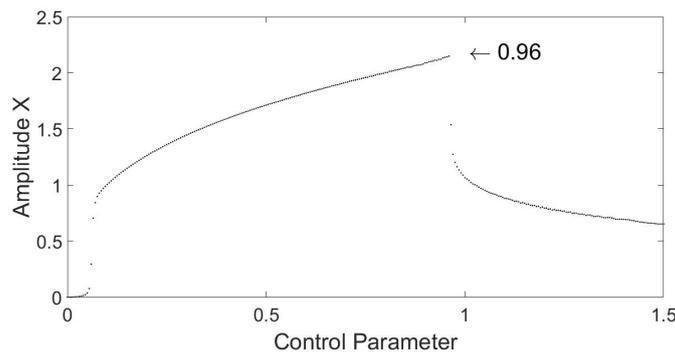


Figure 2: **Curve of Resonance**

According to the Fig. 2 the value of the control parameter affords the resonance is (0,96), because when the system is in resonance the amplitude of oscillation is maximum. Besides, it is noted the Sommerfeld effect, that after the region the resonance, the maximum amplitude of oscillation is lower. This phenomenon happens, in according to Iliuk *et al.* (2011), because in region near of resonant conditions the energy that was applied is consumed to generate large amplitude motions in the structure, but not increase angular velocity in the motor. Then, the motor gets stuck in the resonance and when some more energy is available the speed of motor is higher and the structure's oscillation is lower.

3.2 Displacement and Power Harvesting

Thus, with the value of the control parameter found that achieve the resonance and it is able to verify this behavior of the model to harvest energy and compare to another control parameter, looking to displacement and the power harvesting. Then, it will be two values of the control parameter, both of them near of resonance, one after and another before it.

In Fig. 3 is showed the displacement and the power harvested to the value before the resonance.

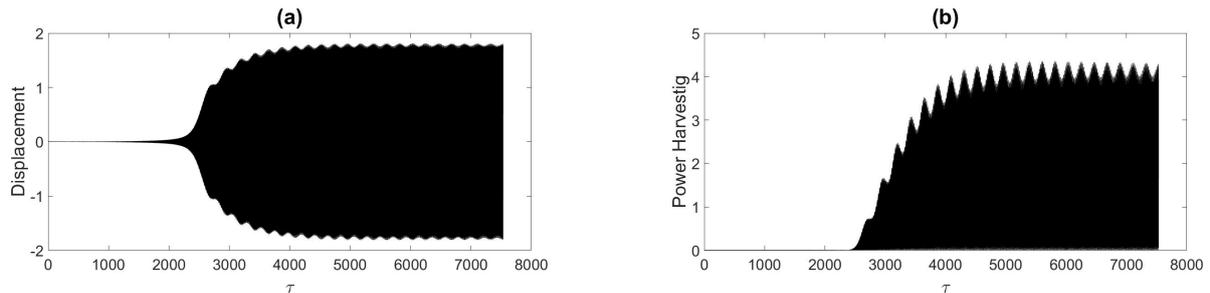


Figure 3: Response for value of μ_1 is equal 0,6. (a) displacement; (b) power harvesting.

And in the Fig. 4, it is showed the displacement and the power harvested to the value after the resonance.

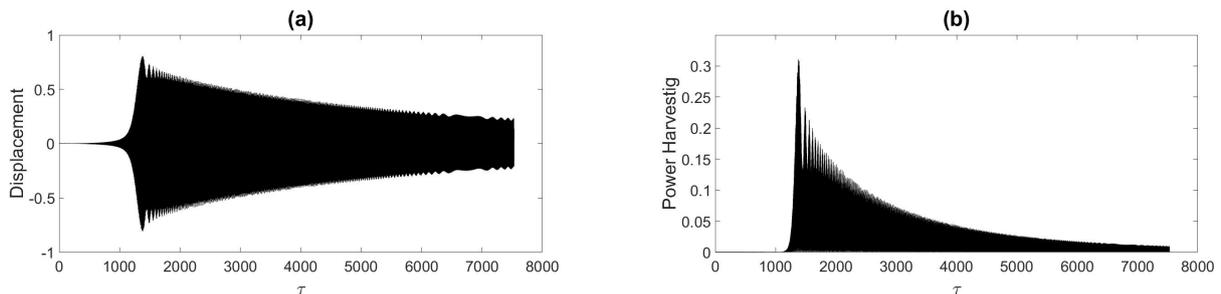


Figure 4: Response for value of μ_1 is equal 1,2. (a) displacement; (b) power harvesting.

Finally, in the Fig. 5, the system is at the resonance.

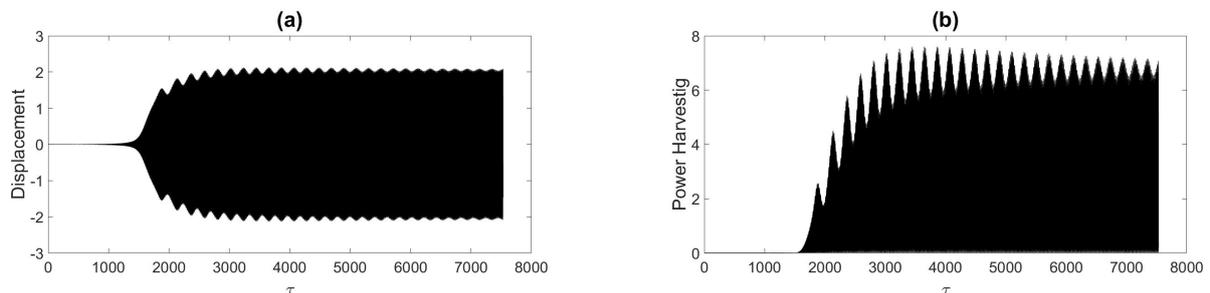


Figure 5: Response for value of μ_1 is equal 0,96. (a) displacement; (b) power harvesting.

Therefore, as foreseen that the power output is higher at resonance than in pre-resonance and post-resonance, due to the Sommerfeld effect, the energy harvester is higher at pre-resonance than at the post-resonance.

3.3 Angular Velocity

Also, a good way to detect the Sommerfeld effect is to see that the angular velocity, as previously mentioned, the velocity angular increase and the displacement decrease, in region of post resonance. This characteristic is seen in Fig. 6.

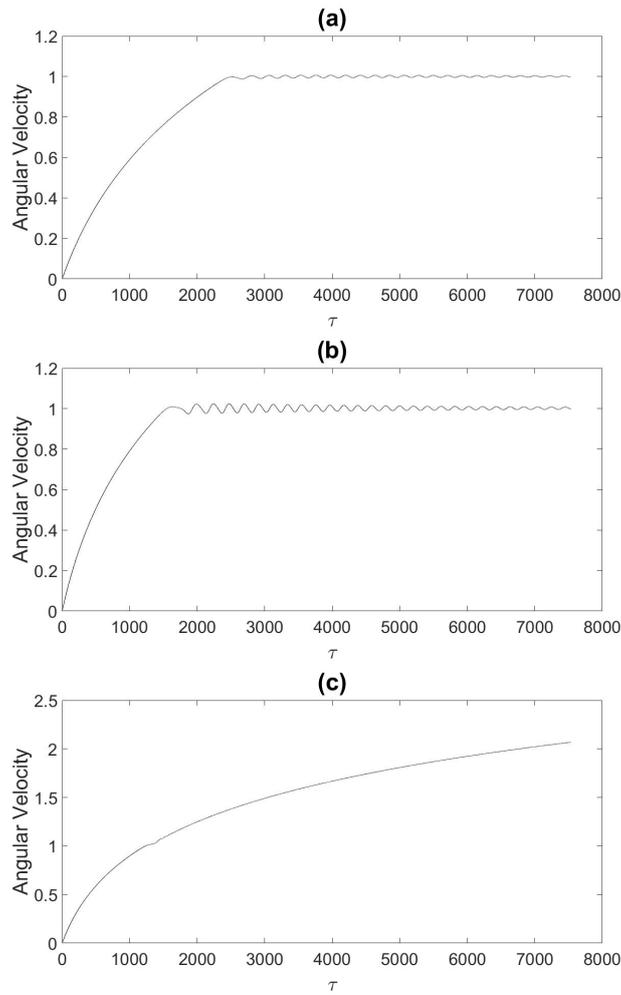
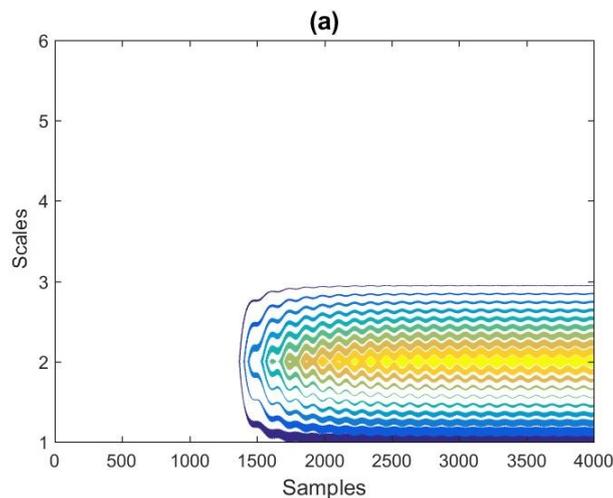


Figure 6: **Response for value of angular velocity for three cases. (a) μ_1 igual à 0.6; (b) μ_1 igual à 0.96; (c) μ_1 igual à 1.2**

Hence, for this model, it can be seen that in region until the resonance, the angular velocity was constant, however, when the system exceeds the frequency of resonance, the angular velocity increase.

3.4 Continuous Wavelet Transform - CWT

Another analysis it was done using a Wavelet Transform, that decompose the signal in different components of frequencies, thus allowing to study each component separately in their corresponding scale. This transformation from domain become some properties with the signal more evident. Thus, conform Fig. 7 is possible to do this analysis.



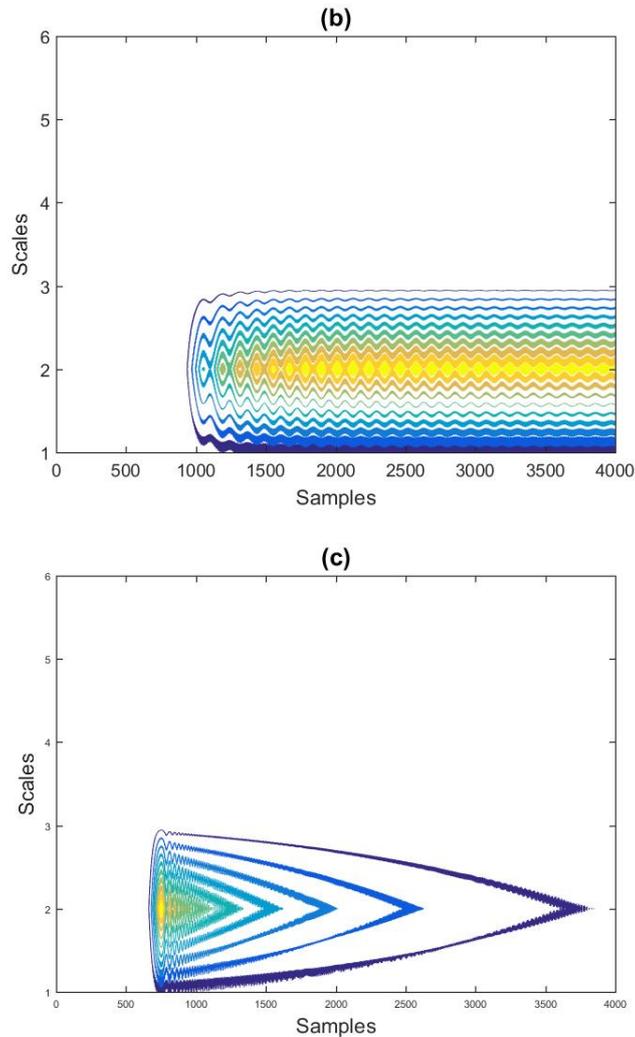


Figure 7: Response of CWT three cases. (a) μ_1 igual à 0.6; (b) μ_1 igual à 0.96; (c) μ_1 igual à 1.2

Therefore, in according with Fig. 7, it shows that the analysis of the signal in scale equals response in time (conform Fig. 3a, 4a and 5a) and when the system is in the region of resonance (Fig. 7b), it is seen that the system had more energy, consequently, will harvest more energy than another region. In addition, the Wavelet analysis can be used to check the Sommerfeld Effect for confirm again this effect detrimental to energy harvesting, because before the resonance harvest more energy than after it.

4. CONCLUSION

In this paper, a mathematical model of an energy harvester and portal frame structure with a non-ideal drive demonstrated the influence of excitation in the energy harvested. The excitation attached in the system through the parameter that control the angular rotation of DC motor across voltage applied. Wherefore, it was possible to analyze the responses for three cases, region of pre-resonance, post-resonance and in the resonance, that the region of the resonance is better to harvest the energy. Besides, it was possible to verify the Sommerfeld effect that occur in the system and accomplish this phenomenon reduce the power harvesting and loss the stability in this structure as said in Iliuk *et al.* (2012). To verify the Sommerfeld Effect was analyzed the angular velocity, that when occur this effect, the displacement of the structure decreases and the angular velocity of DC motor increase. Furthermore, it was used the signal processing techniques based on Continuous Wavelet Transform to check in vibrations systems which condition proposed have more energy and characterization of the Sommerfeld effect, that is an alternative tool to visualize the some proprieties of nonlinear systems. Where can confirm that the system in resonance harvest more energy that over and the Sommerfeld effect is not a good behavior for energy harvesting.

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6. RESPONSIBILITY NOTE

The authors are the only responsible for the content of this work.