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Power Cell Phones Using Smart Structures Application With LQR Controller Simulation in Regenerative Mode

Aguinaldo Soares de Oliveira
Renato Santos de Souza
Marcelo Augusto Volz
Lucas Ascari Salvalaggio

Federal University of Mato Grosso
Rondonopólis – Mato Grosso - Guiratinga, highway Km 06 - ZIP – 78735 - 901
asoares@ufmt.br
syymbolss@yahoo.com.br
marcelo_software@hotmail.com
lucas-salvalaggio@hotmail.com

Abstract. *The capture of energy by the piezoelectric is made of the resonance rise band of the support structure. This paper propose a simulation of a piezo cantilever beam with optimal control system, LQR controller, so that maximize the vibration and reduce driver effort. In this way the resulting net power will be enough to power a mobile phone*

Keywords: *smart structures, modal analysis, piezoelectric elements.*

1. Introduction

One of the technologies that have been investigated for the active control of vibration in flexible structures is the use of piezoelectric elements, piezoelectric actuators and sensors, distributed throughout the structure. According Crawley and Louis (1987), Lee and Moon (1990), Lima, Jr. (1999), Oliveira (2003) and Oliveira (2008), the piezoelectric actuators are usually made from ceramic materials while the sensors are made of polymers. Environmental vibration is random and varies in a wide frequency band and also features low power, Wang and Inman (2012) suggest that the most promising solution to gain efficiency in piezoelectric active control systems are those based on optimal control. This type of control does not increase the frequency band resonance, as the papers presented so far, but is to maximize the energy captured, regardless of the band and frequency. The proliferation of mobile devices such as sensors, transmitters and actuators creates the need for an energy source that does not require physical connections. The mobile phone needs power 0.042 W, Douglas (2015), then a system that captures and converts vibrational energy into electrical energy would be useful.

2. Dynamics equations

The dynamics equations of a structure with piezoelectric elements attached, finite element modeled is given by:

$$\begin{cases} [M_{qq}]\,\{\ddot{q}_i\}+[k_{qq}]\,\{q_i\}+[k_{q\phi}]\,\{\phi_i\}=\{F_S\}+\{F_i\}+\{F_{el}\} \\ [k_{\phi q}]\{q_i\}+[k_{\phi\phi}]\{\phi_i\}=\{Q_s\} \end{cases} \tag{1}$$

In the piezoelectric sensor there isn't voltage applied (Qs = 0). Then the electric potential yielded by sensor is:

$$\{\phi_s\}=-[K_{\phi\phi}]^{-1}[K_{\phi q}]\{q_i\} \tag{2}$$

Replacing the Eq. (2) in the Eq. (1), yields the equation global system for a beam with actuator attached, that is:

$$\left[M_{qq}\right]\{\ddot{q}\}+\left[K^{*}\right]\{q\}=\{F_{s}\}+\{F_{i}\}+\{F_{el}\} \tag{3}$$

where:

$$\left[K_{qq}^{*}\right]=\left[K_{qq}\right]-\left[K_{q\phi}\right]\left[K_{\phi\phi}\right]^{-1}\left[K_{\phi q}\right] \tag{4}$$

$$\{F_{el}\}=-\left[K_{q\phi}\right]\{\phi_{a}\} \tag{5}$$

The system response may be written by the superposition through the relationship:

$$\{q(x,t)\}=[\overline{\chi}]\{\eta(t)\} \tag{6}$$

Applying Eq. (6) in Eq.(3) gives

$$\left[M_{qq}\right][\overline{\chi}]\{\ddot{\eta}(t)\}+\left[K^{*}\right][\overline{\chi}]\{\eta(t)\}=\{\overline{F}\} \tag{7}$$

With:

$$\{\overline{F}\}=\{\overline{F}_{s}\}+\{\overline{F}_{i}\}+\{\overline{F}_{el}\} \tag{8}$$

Pre-multiplying the Eq. (7) by $[\overline{\chi}]^{T}$, we have:

$$[\overline{\chi}]^{T}\left[M_{qq}\right][\overline{\chi}]\{\ddot{\eta}(t)\}+[\overline{\chi}]^{T}\left[K^{*}\right][\overline{\chi}]\{\eta(t)\}=[\overline{\chi}]^{T}\{F\} \tag{9}$$

Or otherwise:

$$[I]\{\ddot{\eta}(t)\}+[\Lambda]\{\eta(t)\}=\{\overline{F}\} \tag{10}$$

of which:

$$[\overline{\chi}]^{T}\left[M_{qq}\right][\overline{\chi}]=[I]=\begin{bmatrix}1 & 0 & \dots & 0\\ 0 & 1 & \dots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \dots & 1\end{bmatrix} \tag{11}$$

and

$$[\Lambda]=[\overline{\chi}]^{T}\left[K^{*}\right][\overline{\chi}]=\begin{bmatrix}\omega_{1}^{2} & 0 & \dots & 0\\ 0 & \omega_{2}^{2} & \dots & 0\\ \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & \dots & \omega_{n}^{2}\end{bmatrix} \tag{12}$$

of which:

$$\{\overline{F}\} = [\overline{\chi}]^T \{F\} \tag{13}$$

$$\{\overline{F}_{el}\} = [\overline{\chi}]^T \{F\} \tag{14}$$

$$\{\overline{F}_i\} = [\overline{\chi}]^T \{F\} \tag{15}$$

$$\{\overline{\chi}_i\} = \frac{1}{\sqrt{\{\chi_i\}^T [M_{qq}] \{\chi_i\}}} \{\chi_i\} \tag{16}$$

Writing the Eq. (9) as the state space and considering the force point is obtained:

$$\{\dot{z}\} = \begin{bmatrix} [0] & [I] \\ -[\Lambda] & [0] \end{bmatrix} \begin{Bmatrix} \eta(t) \\ \dot{\eta}(t) \end{Bmatrix} + \begin{bmatrix} [0] \\ [I]\{\overline{F}_{el}\} \end{bmatrix} \{u\} + \begin{bmatrix} [0] \\ [I]\{\overline{F}_i\} \end{bmatrix} \tag{17}$$

With:

$$[A] = \begin{bmatrix} [0] & [I] \\ -[\Lambda] & [0] \end{bmatrix} \tag{18}$$

and

$$[B] = \begin{bmatrix} [0] \\ [I]\{\overline{F}_{el}\} \end{bmatrix} \tag{19}$$

$$\{F_e\} = \begin{bmatrix} [0] \\ [I]\{\overline{F}_i\} \end{bmatrix} \tag{20}$$

In the space state, we have:

$$\{\dot{z}\} = [A]\{z\} + [B]\{u\} \tag{21}$$

The control vetor uses de feedback state mode, so:

$$\{u\} = -[G]\{z\} \tag{22}$$

The signal minus is degenerative mode, and plus is regenerative mode

The optimum gain matrix [G] is according to:

$$[G] = [R]^{-1} [B]^T [S_r] \tag{23}$$

With: [S_r] Ricatti matrix and [R] weight matrix. The gain feedback matrix optimum, can be divide in optimum gain relative to displacement and velocity, so then:

$$[G]=\begin{bmatrix}G_{\dot{q}} & G_q\end{bmatrix} \tag{24}$$

3. Beam & piezoeletric properties

It was simulated a cantilever beam with piezoelectric attached, whose dimension and properties of beam and piezoelectric element are shown in Tab. 1 and Tab. 2.

Table 1. Beam Dimension and Properties

Properties	*Value*	*Unit*
Length L	1,5	m
Width b	0,075	m
Thickness h	0,075	m
Specify Mass ρ	7800	kg/m^3
Young Module Y	$210x10^9$	N/m^2
Poisson Coefficient ν	0,3	-
Shear Coefficient κ	0,833	-
Transversal Elasticity Module G	$80x10^9$	N/m^2
Area A	$5,625x10^{-3}$	m^2
Inertia Momentum I	$2,6367x10^{-6}$	m^4

Table 2. Piezoelectric Element Dimension and Properties

Properties	Value	Unit
Young Module Y_{pe}	$130x10^9$	N/m^2
Length L_{pe}	0,150	m
Width b_{pe}	0,0750	m
Thickness h_{pe}	0,010	m
Piezoelectric Coefficient d_{31}	$390x10^{-11}$	m/V
Specify Mass ρ	7800	kg/m^3

4. Computer code validation

The dimensionless frequencies are defined by Eq. (21).

$$\lambda_i^2=\omega_i L^2\sqrt{\frac{\rho A}{YI}} \tag{25}$$

The Tab. 3 shows the dimensionless frequencies for a Timoshenko simply support beam. The theoretical results are calculated by Lee and Schultz (2004) with the ratio h / L = 0.05

Table 3. Dimensionless frequencies for a Timoshenko simply support beam

i	Theoretical[1]	FEM – Beam Elements Numbers - h/L=0,05			
		λ_i			
		5	10	20	50
1	3,13498	3,1360	3,1358	3,1358	3,1358
2	6,23136	6,2446	6,2380	6,2372	6,2371
3	9,25537	9,3236	9,2784	9,2727	9,2716
4	12,1813	12,3970	12,2377	12,2156	12,2111
5	14,9926	16,3391	15,1064	15,0451	15,0323

The Tab. 4 shows the dimensionless frequencies for a Timoshenko cantilever beam. The theoretical[2] results are found in the work of Han and Jae-Jung (1999) with the ratio h / L = 0.05. The Fig. 1 shows a cantilever beam with piezoelectric elements attached.

Table 4. Dimensionless frequencies for a Timoshenko cantilever beam

i	Theoretical[2]	FEM – Beam Elements Numbers h/L=0,05			
		λ_i			
		5	10	20	50
1	1,8732	1,8735	1,8735	1,8735	1,8735
2	4,6624	4,6674	4,6660	4,6658	4,6658
3	7,7322	7,7626	7,7463	7,7441	7,7437
4	10,6904	10,7932	10,7273	10,7165	10,7143
5	13,5397	13,6675	13,6165	13,5827	13,5753

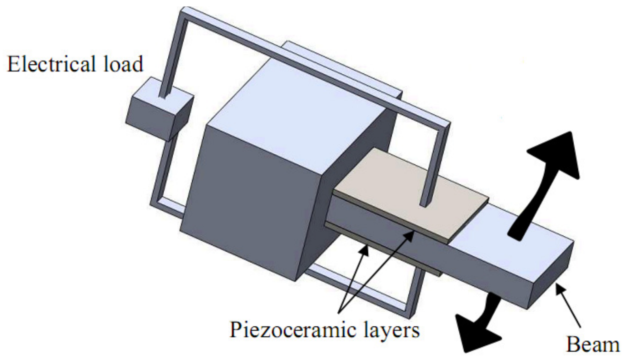

Figure 1. Cantilever beam with actuators, Douglas (2015)

5. Simulation

The fig. 2 shows a third vibration mode of cantilever beam, the fig. 3 shows a regenerative control of the cantilever beam when excited by sine input in third mode, the fig 4 shows a second vibration mode of cantilever beam, the fig 5 shows a regenerative control of cantilever beam when excited by sine input in second mode, the fig 6 shows a first vibration mode of cantilever beam, the fig 7 shows a regenerative control of cantilever beam when excited by sine input in first mode, the fig 8 shows a third vibration mode of bi-supported (simply supported beam) and the fig 9 shows a regenerative mode of bi supported beam (simply supported beam) when excited by sine input in third mode.

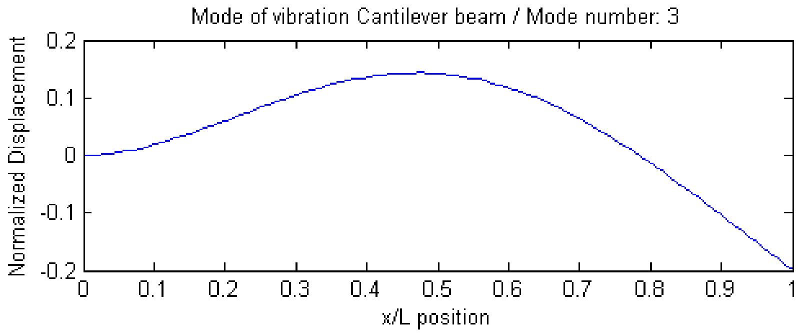

Figure 2. Third vibration mode of Cantilever beam

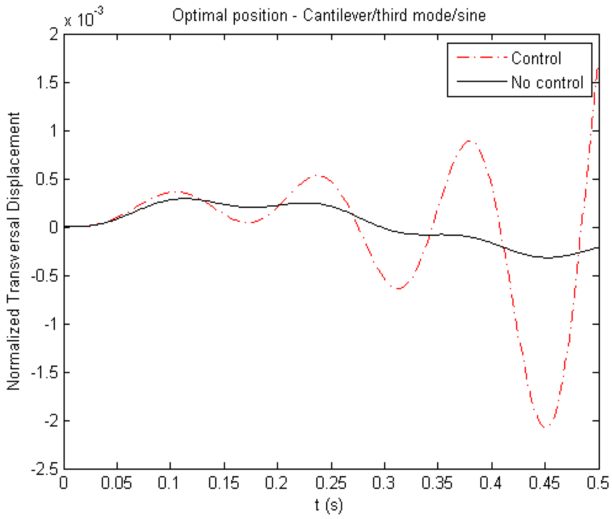

Figure 3. Regenerative control of Cantilever beam excited by input sine/third mode

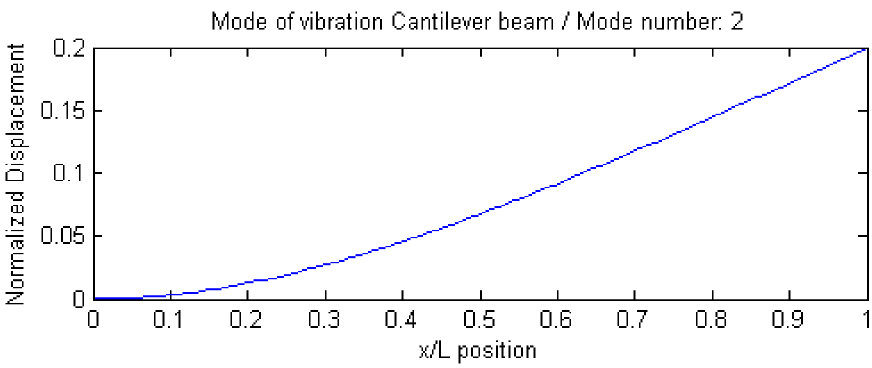

Figure 4. Second vibration mode of Cantilever beam

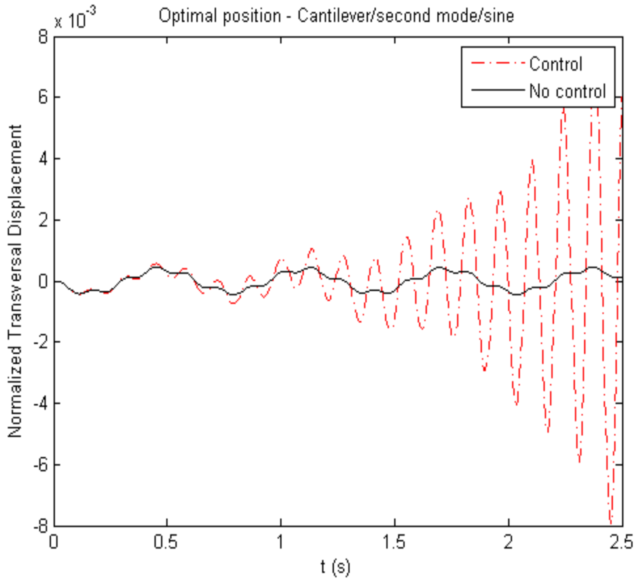

Figure 5. Regenerative control of Cantilever beam excited by input sine/second mode

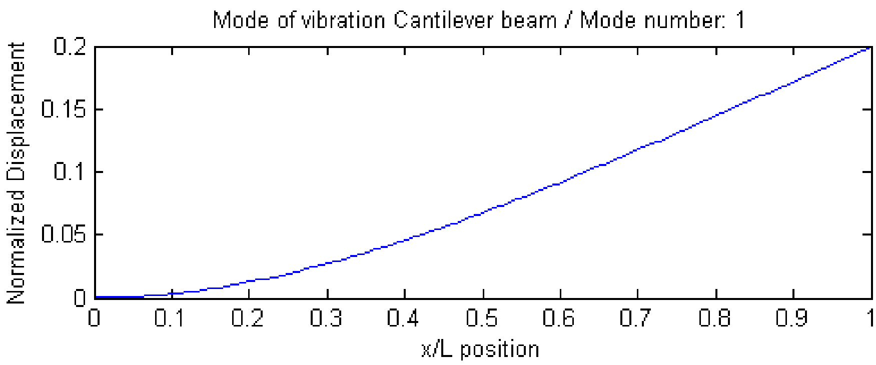

Figure 6. First vibration mode of Cantilever beam

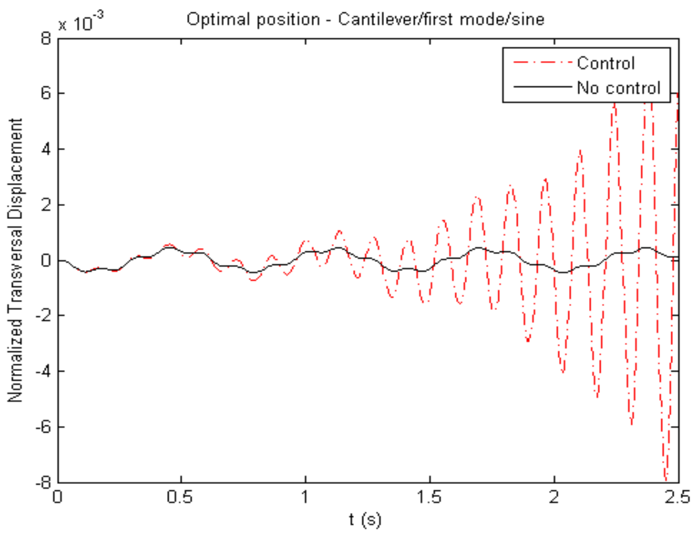

Figure 7. Regenerative control of Cantilever beam excited by input sine/first mode

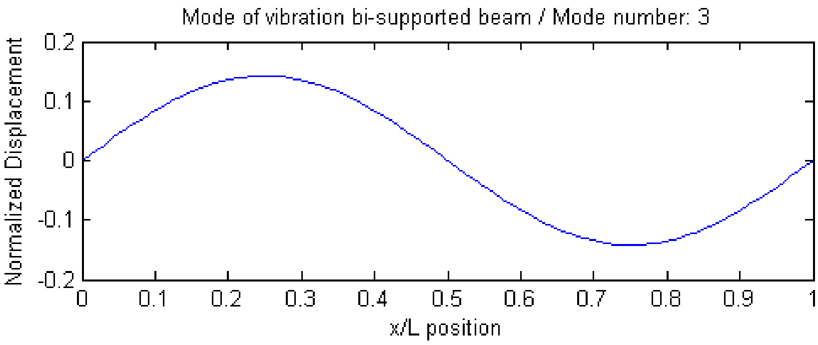

Figure 8. Third vibration mode of bi-supported beam (simply supported)

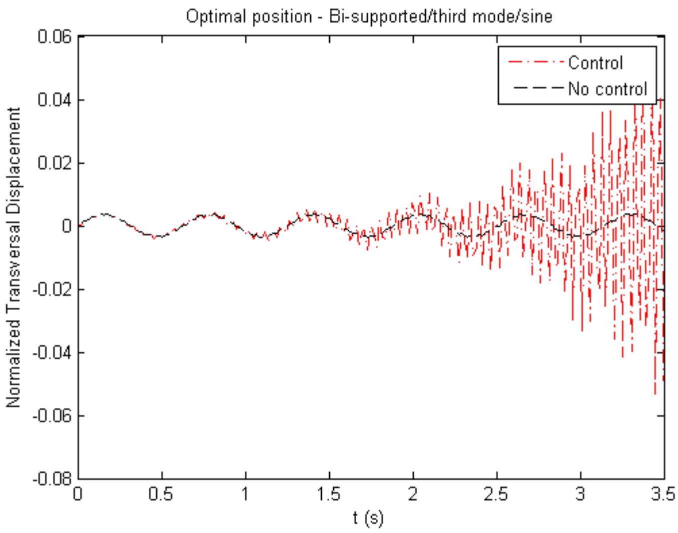

Figure 9. Regenerative control of bi-supported beam (simply supported) excited by input sine third mode

6. Conclusions

This work shows that the regenerative control, signal plus, increases the level of vibration to a certain vibrate mode, unlike the degenerative control, signal minus, that decreases the level of vibration. Increasing the level of vibration, it generates more energy by the direct effect of piezoelectricity, without having to seek the frequency of resonance or changed the parameters of controller. So this mode more energy can be generated and supply a portable devices.

7. Acknowledgements

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8. References

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