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Optimal Linear Control Driven for Piezoelectric Non-Linear Energy Harvesting on Non-Ideal Excitation Sourced

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Abstract. Non-linear energy harvesting system was project to enhance interaction to ambient vibration that is wide band and low power which difficult the design for resonant solution. To improve efficiency of a non-linear design it was project a control system based in optimal linear control (OLC). Applying numerical evaluations it was possible to analyze the kinetic energy from the system as also the resulting output voltage. As main result there was a considerable increase of output voltage due controlled system in comparison to open loop for the same excitation.

Introduction

A piezoelectric material in direct effect behavior converts kinetic energy into electricity and an energy harvesting system utilizes vibration as source to supply electrical power [1]. Most solution for harnessing vibration focus in resonant solution [2] regarding a topology were natural frequency of energy harvesting system is coincident to vibration frequency [3]. Nevertheless ambient vibration is wide band [1, 2, 3] and resonant projects keeping this condition only for a narrow space of time and consequently the efficiency of this solution remains insufficient for their finality [4, 5, 6]. Resonant projects even must deal to low power ambient vibration [1, 2, 3, 4, 5, 6] which hampers small size designs [1, 3]. An answer for this difficulties are located in non-linear solution as proposed by [4, 5, 6], which increase efficiency by rising relation from ambient excitation and energy harvesting system response. Although non-linear has appeared as a better solution it is even insufficient to several applications regarding electrical consumption necessities [7]. A possible solution to enhance energy harnessing can be accomplished by controlled system projects that can improve interaction between excitation source and energy harvesting system vibration.
In this direction this investigation will propose a control project based in optimal linear control (OLC) for their well adjustment to non-linear systems and their robust result to optimization [8, 9, 10]. For this study the excitation is considered as non-ideal were a limited power in controller systems influences the own controller thus the model of movement is added for a feedback term [11, 12].
Considering the paper organization as follow: energy harvesting system model, controller project, efficiency analysis from open loop to controlled system, conclusions and acknowledgements.

Energy Harvester System Dynamic Model

A non-linear energy harvesting system [6] excited by a non-ideal power source [9] is given in Fig. (1). The dynamic model for the proposed non-linear energy harvesting system subject to non-ideal power source is given in the dimensionless Eq. (1), where ζ is damping, χ is piezoelectric mechanical coupling coefficient, Λ is reciprocal of time constant, k is piezoelectric electric coupling coefficient, q is non-ideal excitation and b, r and a refers to non-ideal behavior parameters. The state variable x refers to beam position, z is vibration power source position and ν is voltage resistance.

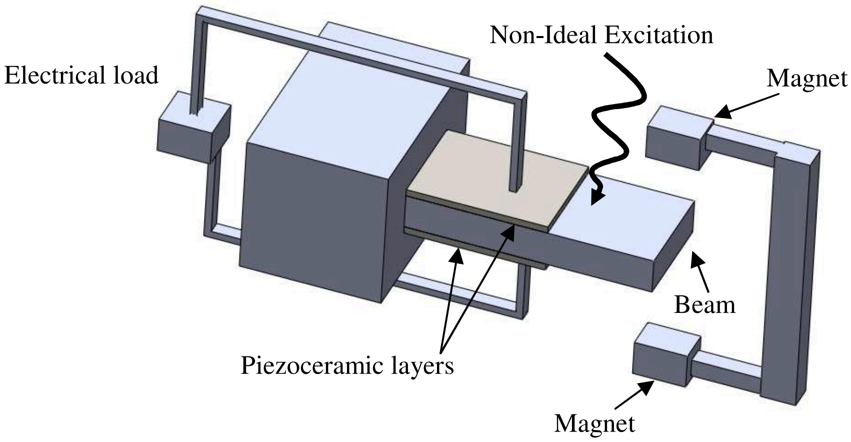


Fig. 1- Non-linear energy harvester system [6].

$$\begin{aligned}
&\ddot{x} + 2\zeta\dot{x} - \frac{1}{2}x(1 - x^2) - \chi v = q(\dot{z}^2 \cos z + \ddot{z} \sin z) \\
&\ddot{z} + b\dot{z} = r\ddot{x} \sin z + a \\
&\dot{v} + \Lambda v + k\dot{x} = 0
\end{aligned} \tag{1}$$

Isolating $\ddot{x}$ e $\ddot{z}$ from Eq. (1) the dynamical model is presented according Eq. (2).

$$\begin{aligned}
&\ddot{x} = \frac{\frac{1}{2}x(1 - x^2) - 2\zeta\dot{x} + \chi v + q\dot{z}^2 \cos(z) + q \sin(z).(a - b\dot{z})}{1 - qr \sin^2(z)} \\
&\ddot{z} = \frac{r \sin(z).(\frac{1}{2}x(1 - x^2) - 2\zeta\dot{x} + \chi v + q{x_4}^2 \cos(z)) + a - b\dot{z}}{1 - qr \sin^2(z)} \\
&\dot{v} = -\Lambda v - \kappa\dot{x}
\end{aligned} \tag{2}$$

Adopting $x_1 = x$, $x_3 = z$ and $x_5 = v$, the space-state form of Eq. (2) is given by equation (3).

$$\begin{aligned}
&\dot{x}_1 = x_2 \\
&\dot{x}_2 = \frac{\frac{1}{2}x_1(1 - {x_1}^2) - 2\zeta x_2 + \chi x_5 + q{x_4}^2 \cos(x_3) + q \sin(x_3).(a - bx_4)}{1 - qr \sin^2(x_3)} \\
&\dot{x}_3 = x_4 \\
&\dot{x}_4 = \frac{r \sin(x_3).(\frac{1}{2}x_1(1 - {x_1}^2) - 2\zeta x_2 + \chi x_5 + q{x_4}^2 \cos(x_3)) + a - bx_4}{1 - qr \sin^2(x_3)} \\
&\dot{x}_5 = -\Lambda x_5 - \kappa x_2
\end{aligned} \tag{3}$$

Optimal Linear Control Project

Optimal Linear Control (OLC) guarantees the linear control application in non-linear systems. A controlled non-linear system is given by Eq. (4) according [10].

$$\dot{y} = Ay + h(y) + Bu, \qquad y(0) = y_0 \tag{4}$$

Were $y \in \Re^n$ is a vector of states, $A \in \Re^{nxn}$ is a matrix of boundary conditions (parameters), which the elements are time dependents, $B \in \Re^{nxm}$ is a constant matrix, $u \in \Re^m$ is a control vector and $h(y) \in \Re^n$ is a vector which the elements are non-linear continuous function, $h(0) = 0$. Should be noted that A chosen is not unique and it influences on the controller efficiency.

For an infinite time interval and A, B, Q and R been matrix of constant elements, the positive defined matrix P is solution from the non-linear algebraic Riccati equation given in Eq. (5).

$$PA + A^T P - PBR^{-1}B^T P + Q = 0 \tag{5}$$

Parameter for non-linear energy harvesting system [6] are given in Table 1 and parameters for non-ideal excitation are given in Table 2 [9].

Table 1- Parameters for Non-Linear Harvester [6].

Parameter	ζ	χ	Λ	κ
Value	0.01	0.05	0.05	0.5

Table 2- Parameters for Non-Ideal Excitation [9].

Parameter	a	b	r	q
Value	2.3	0.5	0.5	0.5

For the system configuration presented in Eq. (3) were calculated the Lyapunov exponents by Wolf method [13] and was identified two positive exponents $\lambda_1 = 0.36272$ and $\lambda_2 = 0.023508$ and the system is considered dynamically chaotic.

Considering the Eq. (3), given parameters and setting up a Jacobian matrix for initial conditions $x_1 = 1, x_2 = 0, x_3 = 0, x_4 = 0$ and $x_5 = 0$, the matrix of states A is given in Eq. (6).

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -1 & -0.02 & 1.15 & 0 & 0.05 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -0.5 & 0 \\ 0 & -0.5 & 0 & 0 & -0.05 \end{bmatrix} \tag{6}$$

For the control project the matrix B, Q and R given in Eq. (7)

$$B = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}, Q \; and \; R = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

Applying optimal linear control definition for matrix A, B, Q and R the solution matrix P is given in Eq. (8).

$$P = \begin{bmatrix} 10.5439 & -0.4347 & -10.9755 & -3.2666 & -0.4884 \\ -0.4884 & 10.0794 & 0.4999 & -7.5791 & 0.0444 \\ -10.975 & 0.4999 & 13.6219 & 3.7565 & 0.5617 \\ -3.2666 & -7.5791 & 3.7565 & 11.8816 & 0.1650 \\ -0.4884 & 0.0444 & 0.5617 & 0.1650 & 1.0272 \end{bmatrix} \tag{8}$$

And the gain vector G is given in Eq. (9).

$$G = [0.2052 \quad 0.4189 \quad -0.2360 \quad -0.3919 \quad -0.0051] \tag{9}$$

Efficiency Analysis

In order to compare open loop system to controlled system according available kinetic energy to be converted to electricity it was computed feedback parameters from the resulting state matrix A_R considering gain vector G as given in Eq. (10).

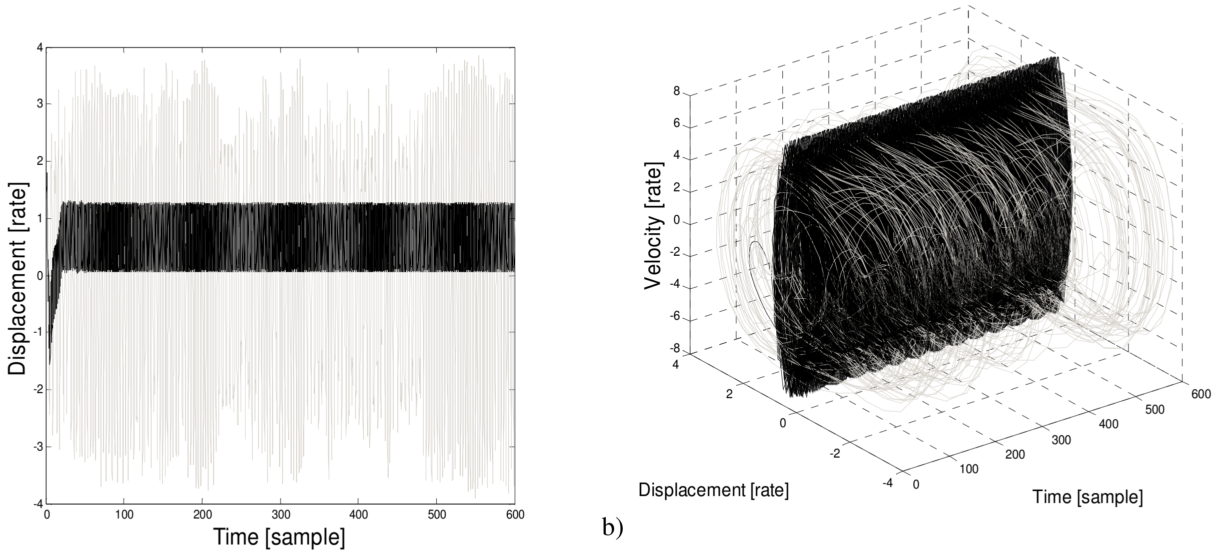
$$A_R = A - B * G \tag{10}$$

Computing the resulting state matrix A_R according Eq. (10) and comparing to matrix A given in Eq. (6) it is possible to determine the feedback parameters from controlled system as given in Table 4.

Table 4- Feedback parameters.

Feedback Parameter	ζ	χ	Λ	κ	a	b	r	q
Value	0.2194	0.0551	0.0449	0.9189	2.300	0.1081	0.500	0.6026

Applying Runge-Kutta fourth order method for solving ordinary differential equations in Eq. (3) and considering open loop parameters given in Table 1 and Table 2 and feedback parameters for controlled system given in Table 4 the efficiency comparison is given in Fig. 4.



a) b)

Fig. 4- Efficiency comparison from open loop to controlled system. Samples form 0 a 600 in interval of 0.1 totalizing 6,000 time samples were (a) displacement rate , (b) phase portrait time sample. Gray line (open loop) and black line (controlled).

The total vibration energy that can be converted in electricity is presented by output voltage x velocity given in Fig. 5.

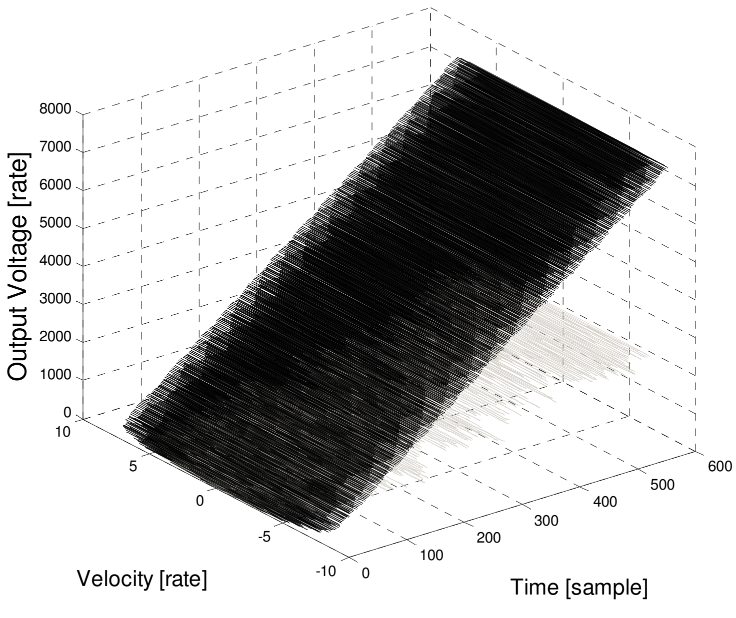


Fig. 5- Efficiency comparison from open loop to controlled system considering output voltage x velocity time sample. Gray line (open loop) and black line (controlled).

Conclusion

According Fig. 5 it is possible to verify that the controlled system has considerable more electrical energy resulting from conversion of kinetic energy than open loop system which leads to the conclusion that the proposed control is efficient for this finality.

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