AIP Conference Proceedings

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Cite as: AIP Conference Proceedings **2425**, 410005 (2022); https://doi.org/10.1063/5.0081364

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Energy Harvesting Capabilities and Dynamics of Pendulum NES

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Abstract. Vibration mitigation is atracting lot of researcher to safegaurd machines and structurs. Energy harvesting along with vibration mitigation gives added advantage of generating enough electrical energy to powerup sensors. Vibration energy harvesting converts vibration into useful electrical energy using suitable trnsduction method. Nonlinear energy sinks (NES) is one of the paasive method to reduce vibration of the structure. Present work considers the dynamics and energy harvesting capability of pendulum NES to mitigate primary structure vibration alongwith electro-magnetic energy conversion. It is observed that the pendulum NES can operate in both oscilating and rotating mode to mitigate primary structure vibration and harvest electrical energy over a wide range of excitation. For smaller excitations the pendulum operates in linear and nonlinear osscilatory mode, for a larger energy input, the pendulum operates in chaotic rotary mode to reduce primary mass vibration. Thus, pendulum can dissipate energies in relatively broad spectrum excitation.

Keywords: nonlinear vibration, electromagnetic energy harvesting, nonlinear energy sink

INTRODUCTION

Various methods of vibration mitigation and control in different machines and structures have been extensively studied since years [1, 2, 3]. Tuned mass damper (TMD) is one of these methods which is passive vibration mitigation [2]. TMDs are attached to a primary system to mitigate its undesirable vibrations. This method is a very popular as it dosnent require any external energy supply [3, 4]. The effectiveness of TMD is limited to peak response of the primary system. Nonlinear energy sink (NES) as vibration absorbers have proven effective in a larger frequency and excitation range due to nonlinear oscillations and energy dissipation [5].

NES refers to an nonlinear secondary small secondary mass attached to a primary mass to mitigate the vibration of primary mass [5]. The energy transfered from primary mass to secondary mass can be converted into useful electric energy to powerup sensors.

Vibration energy harvesting comes handy in this process. Vibration energy harvesting is the process of converting vibration energy into usefull electrical energy. The most common energy transduction methods are piezoelectric, elctromagnetic and elctrostatic to convert vibration into electrical energy [6, 7]. This harvested energy can be used or stored for later use.

This work analyses a pendulum NES consisting of primary mass coupled by a pendulum with electromagnetic conversion system at pivot. Ampli-tude of primary structure, dynamics of pendulum and current output from the

International Conference of Numerical Analysis and Applied Mathematics ICNAAM 2020
AIP Conf. Proc. 2425, 410005-1–410005-5; https://doi.org/10.1063/5.0081364
Published by AIP Publishing. 978-0-7354-4182-8/$30.00

pendulum NES are presented when the system is subjected harmonic excitation. Effect of excitation on energy harvested is carried out inorder to study the effect of this on NES performance. Both oscilating and rotating movement of pendulum is considered.

The paper has been divided into 4 sections. Section Introduction describes the pendulum NES with mathematical model. Results Section deals with the numerical results and discussion. Finally summary of the work with conclusions is presented in conclusion section.

PENDULUM NES MODEL

The pendulum NES model is shown in Fig. 1. The primary system consists of mass M, spring stiffness k and damping c_1. The primary mass also hosts the pendulum with electromagnetic converter. Pendulum has the mass m, mechanical damping c_2 and length l. The harvester consists of a pernamient magnet with magnetic flux density B attached to pendulum which acts as rotor and copper coils with length L and turns density ρ, resistance R and inductance L_0 on stator.

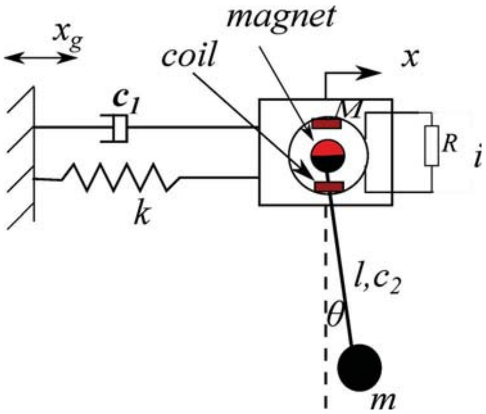

FIGURE 1. Schematic of NES harvester. x_g denotes the frame excitation while x, θ and i correspond to electro-mechanical response vbariables

The elctro-mechanical equations for the system are written as:

$$\begin{aligned} (M+m)\ddot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^2\sin\theta + c_1\dot{x} + kx &= -(M+m)\ddot{x_g}, \\ ml^2\ddot{\theta} + ml\ddot{x}\cos\theta + c_2 l^2\dot{\theta} + mgl\sin\theta + BL\rho i &= -m\ddot{x}_g l\cos\theta, \\ -BL\rho\dot{\theta} - iR + L_0\dot{i} &= 0. \end{aligned} \tag{1}$$

Note that, in general, the interaction between the magnet and and coiles is dependent of an angle θ. However to simplity the calculations we used an effective term $BLri$.

Following nondimensional parameters

$\tau = \omega_1 t$, $\omega_1 = \sqrt{\frac{k}{M+m}}$, $x = Xl$, $\omega_2 = \sqrt{\frac{g}{l}}$, $x_g = X_g\cos(\omega t)$, $\mu = \frac{m}{M+m}$, $\Omega = \frac{\omega}{\omega_1}$, $\eta_1 = \frac{c_1}{m\omega_1}$, $\eta_2 = \frac{c_2}{m\omega_1}$, $f = \frac{X_g}{l}$, $r = \frac{\omega_2}{\omega_1}$, $\delta = \frac{(BLn)^2}{ml^2\omega_1^2 L_0}$, $\zeta = \frac{R}{\omega_1 L_0}$

were used to write a corresponding set of nondimesional equation:

$$\begin{aligned} \ddot{X} + \mu\ddot{\theta}\cos\theta - \mu\dot{\theta}^2\sin\theta + \eta_1\dot{X} + X &= f\Omega^2\cos(\Omega t), \\ \ddot{\theta} + \ddot{X}\cos\theta + \eta_2\dot{\theta} + r^2\sin\theta + \delta I &= f\Omega^2\cos(\Omega t)\cos\theta, \\ -\dot{\theta} - \zeta I + \dot{I} &= 0. \end{aligned} \tag{2}$$

Equations 2 will be solved numerically using ODE45 in MATLAB to obtain results which will be presented in next section.

Results and Discussion

This section presents the numerical results to show the influence of exitation amplitude for different cases of pendulum motion and the energy harvested. The simulation is considered for one thousand time, first 70% of them were eliminate to count transient time. The initial conditions taken were $X = \dot{X} = \theta = \theta = \dot{I} = 0$. The nondimensional parameters used in numerical simulation were; $\mu = 0.2$, $\eta_1 = 0.025$, $\eta_2 = 0.01$, $r = 1$, $\delta = 0.2$, $\zeta = 0.2$.

In order to illustrate simultaneous vibration mitigation and energy harvesting from NES frequency reponse curves were shown in Fig. 2. Figure 2 (a) shows amplitude frequency response curve of primary mass M, the vibration amplitude at resonant frequency is attenuated due to introduction of pendulum NES as expected. The energy harvesting capability is shown in Fig. 2 (b), electric current is generated due to pendulum movement at wider frequency range.

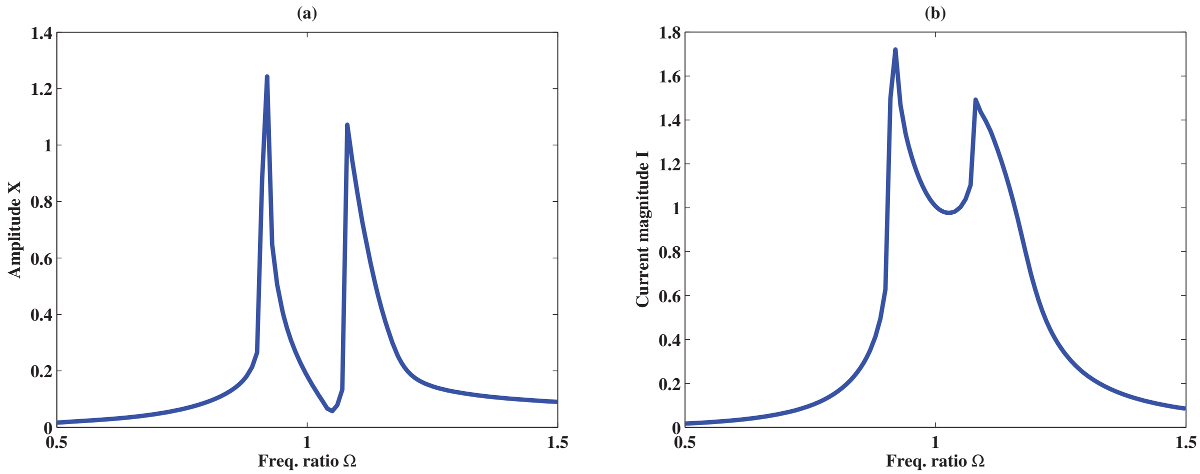

FIGURE 2. Frequency response curves f=0.04 (a) Amplitude response of primary system, (b) Current generated by pendulum NES.

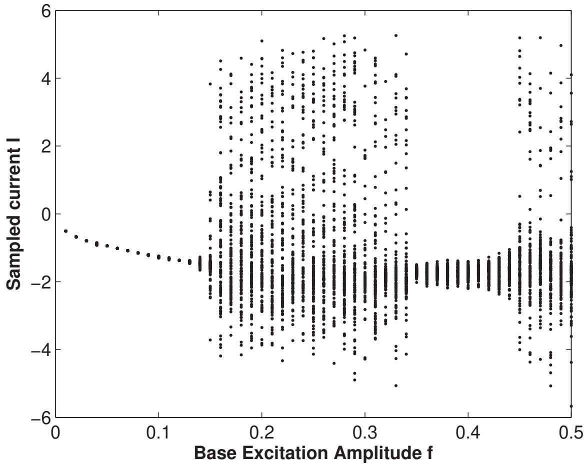

FIGURE 3. Bifurcation of current generated via excitation amplitude $\Omega = 1$

The different cases of pendulum motion is illustrated in bifurcation diagram as sfown in Fig. 3, the bifurcation diagram shows the behaviours of current generated by pendulum against the excitation amplitude are clearly dis-

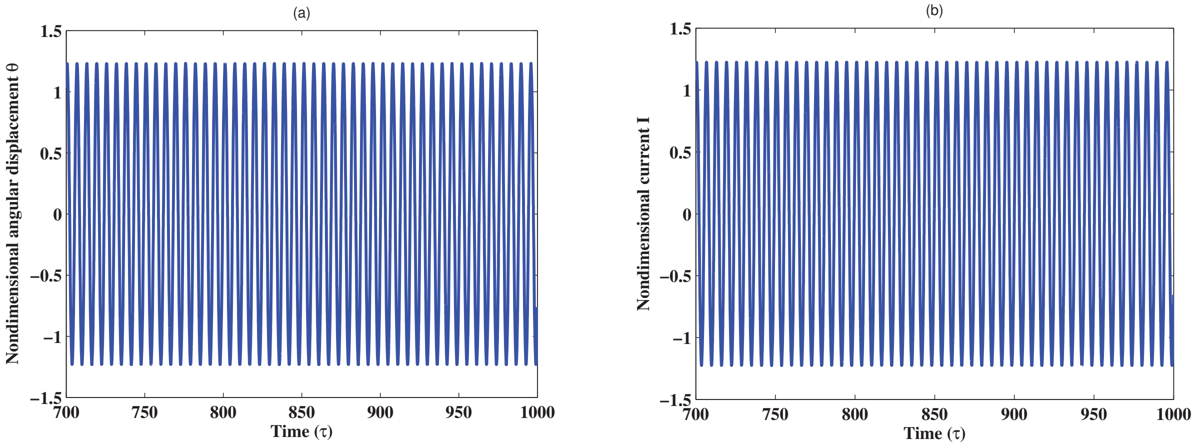

FIGURE 4. Time histories at $f = 0.08$ and $\Omega = 1$ (a) Pendulum angular displacement, (b) Current generated.

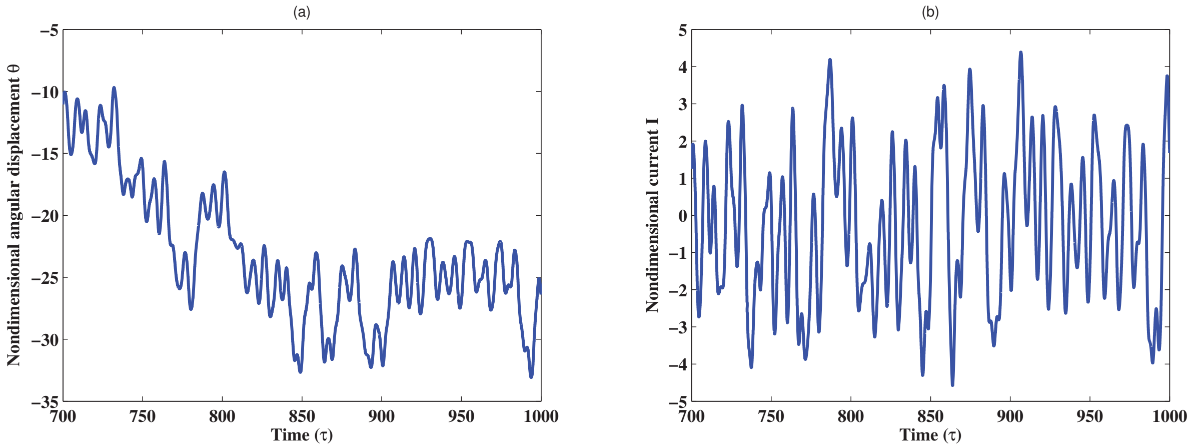

FIGURE 5. Time histories at $f = 0.2$ and $\Omega = 1$ (a) Pendulum angular displacement, (b) Current generated.

tinguished. The results shows that there exist different periodic and chaotic regions. The chaotic region consists of osccilation and rotation motion of pendulum.

Considerating the dynamics of the system, the output current I was tested for selected values of the excitation amplitude f. Figure 4 presents the results of periodic swinging pendulum at $f = 0.08$. In this case, the current has uniform value I = 1.2. The time history of the current is shown in Fig4 (b). The negative current value results from the osccilation pendulum in negative direction.

Figure 5 shows the results from chaotic rotation of pendulum. Anticlosckwise rotation of pendulum can be observed from Fig. 5 (a). A higher magnitude of current can be generated from rotataing pendulum as shown in Fig. 5 (b).

CONCLUSION

The paper presented the numerical study of the pendulum NES to mitigate primary mass vibration and harvest energy simultaneously. The rotating pendulum has shown promising performance. Based on the results, it can be concluded that for properly selected parameters vibration mitigation and energy harvesting can be done simultaeously. The results present basic version of bigger future work for a metastructure with multiple pendulums.

ACKNOWLEDGMENTS

P V M acknowledges VGST (Grant no. KSTePS/VGST-K-FIST L2/GRD No.765) and MIS acknowledges VGST (Grant no. KSTePS/VGST-K-FIST L1/GRD No.387). P V M and G L acknowledges ehDIALOG (DIALOG 0019/DLG/2019/10).

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