

Integrated bistable generator for wideband energy harvesting with optimized synchronous electric charge extraction circuit

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Abstract. Bistable generators have been proposed as potential solutions to the challenge of variable vibration frequencies. In the authors' previous works, a specific BSM (Buckled-Spring-Mass) harvester architecture has been suggested. It presents some properties of interests: simplicity, compactness and wide bandwidth. Using a normalized model of the BSM generator for design and optimization at different scales, this paper presents a new integrated BSM bistable generator design with the OSECE (Optimized Synchronous Electric Charge Extraction) technique which is used for broadband energy harvesting. The experimental results obtained from an initial prototype device show that the BSM generator with the OSECE circuit exhibits better performance for low coupling cases or reverse sweep excitations. This is also confirmed by simulations for the proposed integrated generator. Good applications prospective is expected for the bistable generator with the nonlinear OSECE circuit.

1. Introduction

Autonomous wireless sensors are widely used for structures, environment, earthquake and health monitoring. They bring great facilities and conveniences to a lot of technology fields. To get rid of the battery limitation on the devices' life span and achieve less maintenance cost, vibration, light, heat and so on are now considered as the possible power sources to supply clean and renewable energy. Harvesting the vibration energy with the piezoelectric materials is one of the favorable ways because of the feasibilities of integrating the piezoelectric materials into devices [1].

To make the energy harvester robust, efficient and adaptable for different vibrations environments, one important and desired property is the wide bandwidth. Taking advantage of nonlinearities into the mechanical design is an effective way to increase the generators' operating bandwidth [2-3]. Among the developed nonlinear generators, bistable oscillators show some better performances. Cottone et al. [4] investigated a cantilever beam using a tip magnet which is arranged in face of another fixed magnet. Compared to a linear cantilever generator, a power increase of 400%-600% is obtained. The performance improvements and wide bandwidth property are also observed for chirp excitations [5] and noise excitations [6]. Buckled beams [7][8] or plates [9] are considered as another way to realize bistable oscillators. More recently, a BSM (Buckled-Spring-Mass) harvester is also proposed by the authors [10]. Experimental investigations show that this BSM bistable generator has the desired wideband property and it is simple and compact. Moreover, a developed model is able to well describe the harvester dynamics which simplify the optimization procedure of the design.

Apart from the mechanical design optimization, extraction interface circuits are another critical subject to improve the harvesting efficiency. To enhance the harvesting efficiency and decrease the load dependence, many nonlinear switching techniques are developed [11]. An OSECE (Optimized



Synchronous Electric Charge Extraction) technique has been proposed by Wu et al. [12] recently. In this new circuit, the switching strategy is much simpler while providing higher performance and maintaining the low impedance dependence property for a wide load range.

In this paper, a new integrated BSM generator design is proposed to be used with the OSECE technique. The combination of the bistable generator and the nonlinear harvesting circuit is believed to bring better performance.

2. Design and Analysis

2.1. Integrated BSM generator

The miniaturized BSM generator and its assembling platform have been developed and is presented in figure 1. Its unique mono-block design allows the compactness and reliability to be optimized. Four beams are used as flexible hinges which will be demonstrated as critical parts of the device hereafter. An inertial mass is located at the maximum displacement position to improve its effect whereas the piezoelectric elements strain is maximized using an elliptical shape geometry to amplify the force. Two piezoelectric stack elements are inserted under a pre-stress condition. The interdigital electrodes are separately connected to the positive and negative poles.

Before operations, the deformation of the frame is tuned by two dedicated screws on the assembling platform. The device is statically set to a buckled position and the mass then moves from the center position to a new equilibrium position as indicated by the dashed line in figure 1.

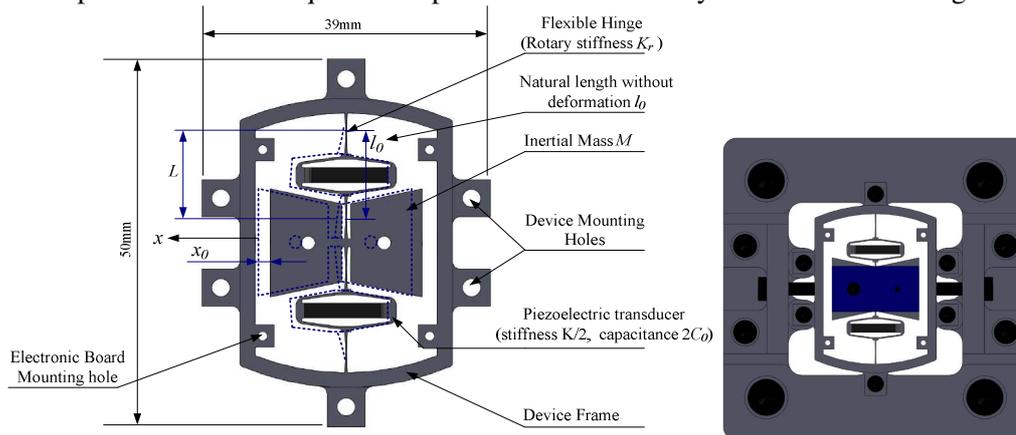


Figure 1. Integrated BSM generator and its assembling platform

According to the analysis in [2], the governing equations of the integrated BSM generator are expressed as:

$$\begin{cases} M\gamma = M\ddot{x} - \frac{Kx_0^2}{2L^2}x + \frac{K}{2L^2}x^3 + d\dot{x} + \alpha V_p \frac{x}{L} \\ I = \frac{\alpha}{L}x\dot{x} - C_0\dot{V} \end{cases} \quad (1)$$

where α is the piezoelectric coefficient; d is the damping coefficient while the other parameters are shown in figure 1. The initial buckled position is:

$$x_0 = \sqrt{l_0^2 - L^2 - \frac{8K_r}{K}} = \sqrt{\Delta l \times L - \frac{8K_r}{K}} \quad (2)$$

$\Delta l = l_0 - L$ represents the initial deformation required to be less than allowed maximum deformation of the piezoelectric transducer which limit the available displacement of the generator. It is clear that the flexible hinges play a critical role in the design. If K_r is too high, x_0 becomes negative, meaning that a bistable behaviour cannot be obtained. To satisfy the requirement, four long thin beams in Fig.1 are optimized to ensure low K_r as well as acceptable maximal stress. Adjustable PTFE stoppers have been

added for safety purpose. Additional mass can be added to optimize the performances for a given vibration environment.

For a more generic scope of the model, normalization is performed using the following definitions:

$$\varepsilon = \frac{x_0}{L}, \quad \bar{x} = \frac{x}{L}, \quad \omega_0 = \varepsilon \sqrt{\frac{K}{M}}, \quad \xi = \frac{d}{2\varepsilon\sqrt{KM}}, \quad \bar{I} = \frac{I}{\alpha\varepsilon L} = \frac{I}{\alpha x_0}, \quad \bar{V} = \frac{V_p C_0}{\alpha\varepsilon L} = \frac{V_p C_0}{\alpha x_0}, \quad k^2 = \frac{\alpha^2}{\alpha^2 + KC_0}, \quad \bar{\gamma} = \frac{\gamma}{L} \quad (3)$$

Then equation (1) can be written as:

$$\begin{cases} \bar{\gamma} = \ddot{\bar{x}} - \frac{1}{2}\omega_0^2 \bar{x} + \frac{1}{2}\frac{\omega_0^2}{\varepsilon^2} \bar{x}^3 + 2\xi\omega_0 \dot{\bar{x}} + \frac{k^2}{1-k^2} \frac{\omega_0^2 \bar{x}}{\varepsilon} \bar{V} \\ \bar{I} = \frac{\bar{x} \dot{\bar{x}}}{\varepsilon} - \bar{V} \end{cases} \quad (4)$$

For the BSM bistable harvester architecture, there are four critical dimensionless parameters: buckled level (ε), the electromechanical coupling coefficient of the piezoelectric components (k^2), the damping coefficient (ξ) and the characteristic frequency (ω_0).

2.2. OSECE technique

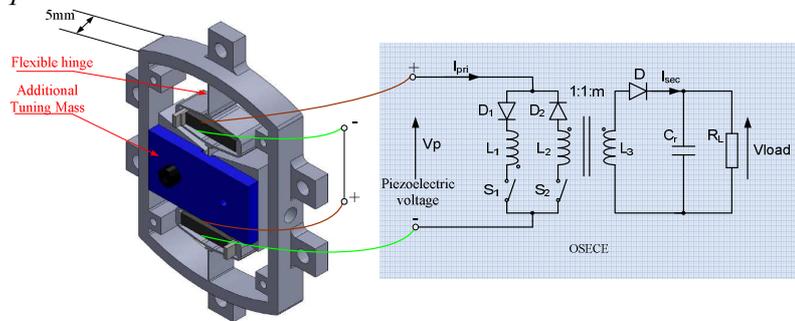


Figure 2. OSECE circuit for the integrated BSM generator

To achieve high harvesting efficiency, the nonlinear OSECE technique is selected to be used with the proposed generator as shown in figure 2. It is based on the SECE circuit with a simpler switching operation strategy. The switch S_1 is closed at the positive maximum of V_p while S_2 is kept open. As V_p arrives at the negative maximum, the status of the switches are inverted (S_1 open, S_2 closed). In this way, one part of the electric energy of the piezoelectric elements is extracted to the load and the rest is preserved at the same time for future extraction. As a result, the energy harvesting efficiency can be enhanced. Compared with the bistable generator with standard circuit, the generator's performance is expected to be improved with OSECE circuit.

3. Experimental and numerical investigations

The principle of the BSM generator was first validated using an initial large scale prototype by experiment and simulation. With the confirmed model, numerical investigations are performed for the proposed integrated miniaturized BSM generator.

3.1. Principle validation

Figure 3 shows the initial prototype for the model validation. It is composed of two piezoelectric transducers (APA120S, CEDRAT Technologies©), four PTFE flexible hinges and an inertial mass (45.8g). This device is subject to a chirp excitation of 4m/s^2 (4Hz-44Hz). The average harvested power values over the whole forward sweep and reverse sweep are separately calculated for the two cases of OSECE circuit and standard circuit. To investigate the performances for different coupling levels, an additional serially connected capacitance is used with the piezoelectric components to change the k^2 value. Tests are repeated for several k^2 cases and the average harvested power is plotted in figure 4.

When k^2 is low, the OSECE technique performs better than the standard circuit for both forward and backward sweeps. As k^2 increases, the energy extracted by the OSECE circuit during each switching process is enlarged. The OSECE's damping effect on the generator's motion becomes

stronger for the forward sweeps and the harvested power is reduced because of the suppression on the motion. The damping effect exceeds the enhancing effect. Therefore, the standard circuit harvests more energy in the cases of forward sweep and high k^2 . The situation is slightly different for the reverse sweeps because the damping effect has less influence on the motion responses. More power is obtained for OSECE circuit unless k^2 is much higher to exert more significant damping. The model is validated considering the good agreement between experiments and simulations.

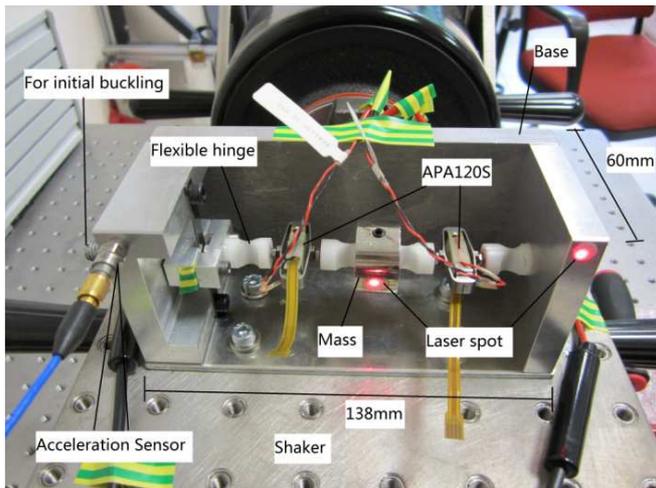


Figure 3. Initial prototype for the model validation.

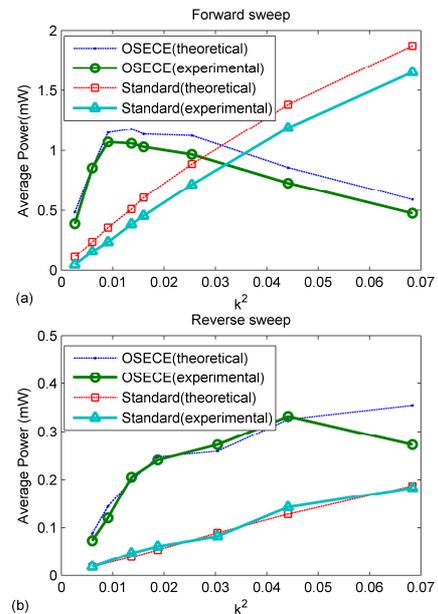


Figure 4. Average harvested power versus k^2 for chirp signal.

3.2. Numerical investigation for the proposed integrated generator

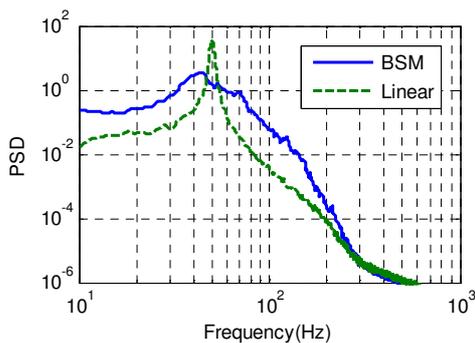


Figure 5. PSD of the piezoelectric voltage for the bistable and linear generators.

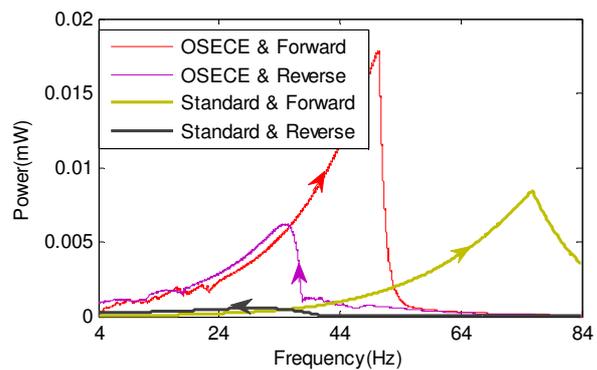


Figure 6. Power response of the integrated BSM generator for OSECE and standard circuit. The arrows represent the frequency sweeping direction.

The performance of the proposed integrated generator can be evaluated by the model. Simulations are done using the parameters listed in Table 1.

Table 1. Simulation Parameters for the integrated BSM generator

$M(g)$	$L(mm)$	$K(N/m)$	$x_0(mm)$	$C_0(\mu F)$	$\alpha(N/V)$	$d(N \cdot s/m)$
15	11.17	4e5	0.061	0.125	0.11	0.14

A bandlimited noise excitation (white noise passing by a 10Hz-200Hz Butterworth filter, RMS 5m/s^2) is first used to confirm the wideband property (the piezoelectric component is kept open with no load). The PSD (Power Spectrum Density) of the piezoelectric voltage for the BSM integrated generator and the linear equivalent generator is shown in figure 5. It is clearly demonstrated that the bistable generator has a much wider bandwidth than the linear equivalent one.

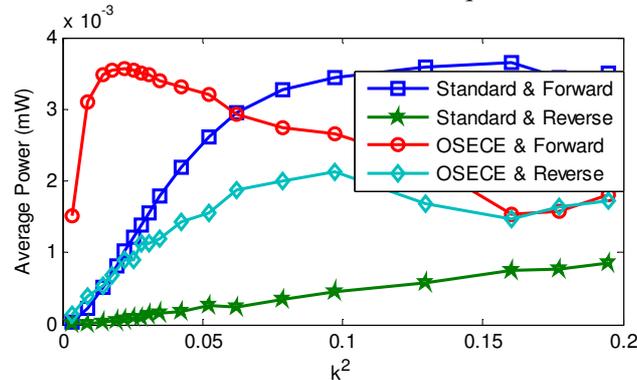


Figure 7. Average harvested power vs k^2 for OSECE and Standard circuit.

The performance of the combination of the integrated generator and the OSECE circuit is then investigated for chirp excitations (10m/s^2 , 4Hz-84Hz). As is done for the initial prototype, a serial capacitance is supposed to connect to the piezoelectric element. The power response for $k^2=0.042$ is plotted and compared with the power response for the standard circuit in figure 6. More power is harvested for OSECE over most excitation frequencies. By changing k^2 in the similar way, the harvested power for different k^2 values are simulated and calculated in figure 7. Similar to the results in figure 4, better performance is achieved for low coupling and reverse sweep cases.

4. Conclusion

In this paper, an integrated BSM generator is proposed. It is used with the OSECE circuit to provide efficient and wideband energy harvesting. The principle is first validated with an initial prototype by experiments and simulations then simulations are performed for the integrated BSM generator. The results show that the combination of the BSM generator and the OSECE circuits enhances the harvested power for low coupling cases as well as reverse sweep excitations. The wideband property of the proposed BSM generator is also presented. This research is believed to be useful for the developing of the wideband generator.

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