Experimental verificatio of load resistance switching for global stabilization of high-energy response of a nonlinear wideband electromagnetic vibration energy harvester

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Abstract. This paper presents an experimental verificatio of a self-excitation control of a resonance-type vibration energy harvester with a Duffing-type nonlinearity which is designed to perform effectively in a wide frequency range. For the conventional linear vibration energy harvester, the performance of the power generation at the resonance frequency and the bandwidth of the resonance peak are trade-off. The resonance frequency band can be expanded by introducing a Duffing-type nonlinear oscillator in order to enable the harvester to generate larger electric power in a wider frequency range. However, since such nonlinear oscillator can have multiple stable steady-state solutions in the resonance band, it is difficult for the nonlinear harvester to maintain the high performance of the power generation constantly. The principle of self-excitation and entrainment has been utilized to provide the global stability to the highest-energy solution by destabilizing other unexpected lower-energy solutions by introducing a switching circuit of the load resistance between positive and the negative values depending on the response amplitude of the oscillator. It has been experimentally validated that this control law imparts the self-excitation capability to the oscillator to show an entrainment into the highest-energy solution.

1. Introduction

Vibration energy harvesting is a micro-power generation technique using a mechanical oscillator with a certain transduction mechanism which is designed to resonate with the environmental vibration source to collect unused or wasted mechanical energy and convert it to electric energy. The conventional vibration energy harvester with a single-degree-of-freedom linear oscillator, however, has a narrow bandwidth because of the power-bandwidth trade-off. One of the most promising nonlinear approaches is Duffing-type harvesters that uses a nonlinearly spring oscillator to widen the resonance frequency band [1, 2, 3, 4, 5]. This idea is an attempt to develop a single-degree-of-freedom energy harvester which can respond largely in a wide frequency range by folding the resonance peak toward the higher (lower) frequency direction by utilizing a hardening (softening) spring instead of the linear one. This type of nonlinear oscillator, however, can have two or more stable solutions with different amplitude in the resonance band when it is subjected to a sinusoidal excitation. It is difficult to keep the response on the highest energy branch because initial conditions determines which solution the response converges. In most literature, this difficulty is recognized as a fatal limitation of this type of nonlinear energy harvesters [1]. In the previous study [6] presented by the authors, a concept of a nonlinear energy harvester in which only the highest energy solution is global stabilized has been proposed. This is done by destabilizing other possible stable solutions by introducing a switching control circuit that switches the load resistance

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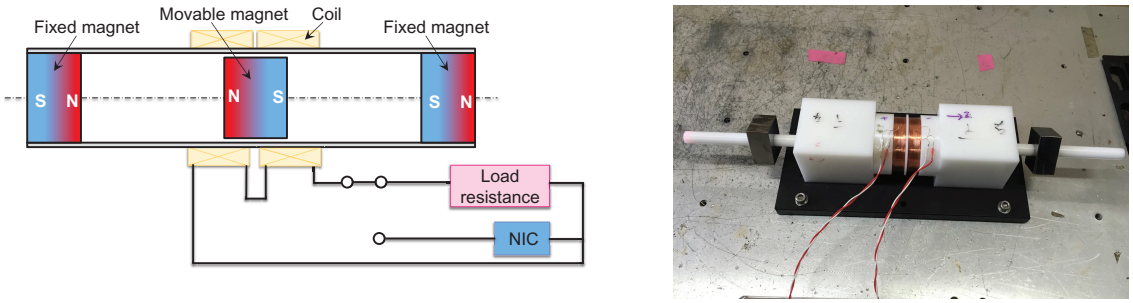


Figure 1. Schematic illustration and photograph of prototype harvester.

between positive and negative values depending on the response amplitude. In the article [6], the validity of the concept was examined by theoretical and numerical analyses, but experimental studies have not been presented. This study aims to conduct an experimental verificatio of the proposed concept by using a conceptual prototype of the proposed harvester. The response of the harvester subjected to the sinusoidal excitation is examined for the cases of with and without the load resistance switching.

2. Prototype design

2.1. Nonlinear oscillator

The prototype of the nonlinear vibration energy harvester investigated in this study is a single-degree-of freedom oscillator with an electromagnetic transducer followed by a load circuit as schematically illustrated in figur 1. It consists of a plastic cylinder with a diameter of 0.041 m and a length of 0.046 m, which has a pair of permanent magnets mounted at both ends and a movable permanent magnet enclosed inside which is guided in the axial direction by a pair of linear bearings. The polarities of the magnets are set such that the movable magnet receives repulsive forces from the fi ed magnets. A copper wire is wound outside the cylinder to form a 500-turn solenoid coil followed by another 500-turn coil in the reverse direction. This arrangement allows the movable magnet not only to perform as an inertial mass of a nonlinear hardening oscillator but also to as an electromagnetic transducer. The transducer is connected to the load circuit, through which the electric power induced by the transducer is transmitted and delivered to the output load. For simplicity, it is assumed that all the circuits used in this study are represented by an equivalent load resistance R serially connected to the internal resistance of the transducer R_g; hence, the output power of the harvester can be evaluated via the power consumption at the resistance R. The photograph of the prototype harvester is also shown in figur 1.

The equation of motion of the prototype harvester is given by

$$m\ddot{x}(t) + \left(c + \frac{\Phi^2(x(t))}{R + R_g}\right)\dot{x}(t) + F(x(t)) = -mu_a \cos \omega t \tag{1}$$

where x is the relative displacement of the mass and u_a is the amplitude of the input acceleration, further, m and c denote the inertial mass and the mechanical damping coefficient, respectively. The functions $\Phi(x)$ and $F(x)$ are the electromechanical force factor, and the restoring force of the magnetic nonlinear spring, as functions of the relative displacement, respectively.

The restoring force $F(x)$ is modeled by following the approximated formulation presented by Vokoun et al. [7] as

$$F(x) = \frac{\pi\mu_0 M^2 r^4}{4} \sum_{j,k=0}^{1} (-1)^{j+k} \left[\frac{1}{(d - x + jh_{fix} + kh_{mov})^2} - \frac{1}{(d + x + jh_{fix} + kh_{mov})^2}\right] \tag{2}$$

where μ_0, M, r, d, h_{fix}, and h_{mov} are the permeability of vacuum, saturation magnetization of the magnets, radius of the magnets, gap between the fi ed magnet and the movable magnet when the latter is in the

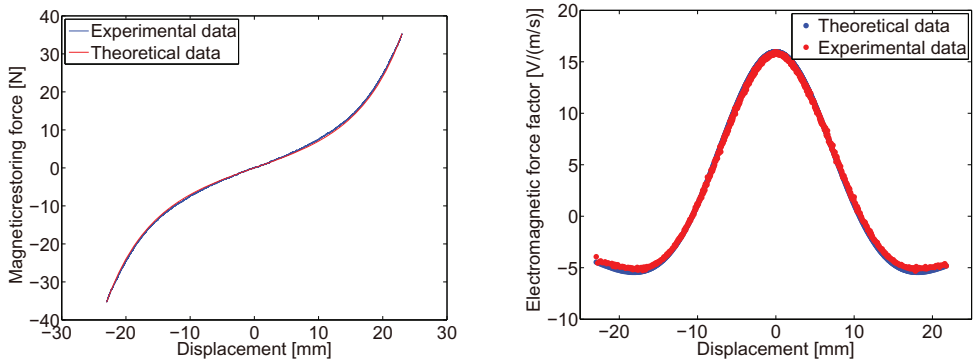


Figure 2. Experimentally identifie functions.

neutral position, thickness of the fi ed magnet, and thickness of the movable magnet, respectively. The electromagnetic force factor $\Phi(x)$ is formulated as

$$\Phi(x) = -\frac{\pi D_{\mathrm{c}}^2}{4} B_{\mathrm{rmov}} \sum_{n=1}^{N} \left[\frac{D_{\mathrm{mov}}^2}{\left\{ 4\left(x + \frac{h_{\mathrm{mov}}}{2} - x_n \right)^2 + D_{\mathrm{mov}}^2 \right\}^{3/2}} - \frac{D_{\mathrm{mov}}^2}{\left\{ 4\left(x - \frac{h_{\mathrm{mov}}}{2} - x_n \right)^2 + D_{\mathrm{mov}}^2 \right\}^{3/2}} \right] \tag{3}$$

All the parameters in equations (2) and (3) were experimentally identified The identifie functions are plotted in figur 2 compared with the experimental data.

2.2. Load switching circuit

Since the nonlinear oscillator described above has strong hardening effect, it has two stable steady-state solutions in the resonance band. Because the initial conditions determine which solution emerges, it is difficult for this nonlinear harvester to maintain the high performance of the power generation constantly. In the study done by Masuda et al. [6], the principle of self-excitation and entrainment has been utilized to provide the global stability to the highest-energy solution by destabilizing other unexpected lower-energy solutions. They proposed to introduce a switching circuit of the load resistance between positive and the negative values depending on the response amplitude of the oscillator as follows:

$$R = \begin{cases} R_{positive} & (a \geq a_\theta) \\ R_{negative} & (a < a_\theta) \end{cases} \tag{4}$$

where a is the displacement amplitude of the oscillator, and a_θ is a threshold value. $R_{positive}$ is the load resistance, while $R_{negative}$ is a negative resistance which performs as a energy source to excite the oscillator. This control law imparts the self-excitation capability to the oscillator to perform an entrainment into the highest-energy solution.

In this study, the negative lord resistance is implemented by using a negative impedance converter (NIC) circuit. The response of the oscillator is measured by a laser displacement sensor, which is fed to the control circuit with a microprocessor (mbed LPC1768) which calculates the amplitude of the displacement to perform the load resistance switching as given by equation 4. The switching circuit is controlled by a switching circuit consisting of FET semiconductor switches.

3. Experimental verificatio

An experimental verificatio of this concept of global stabilization was carried out using an experimental setup depicted in figur 3. The prototype harvester described above was mounted on a single axis

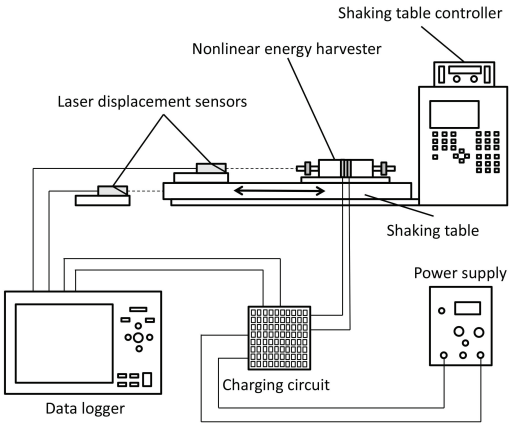


Figure 3. Experiment setup.

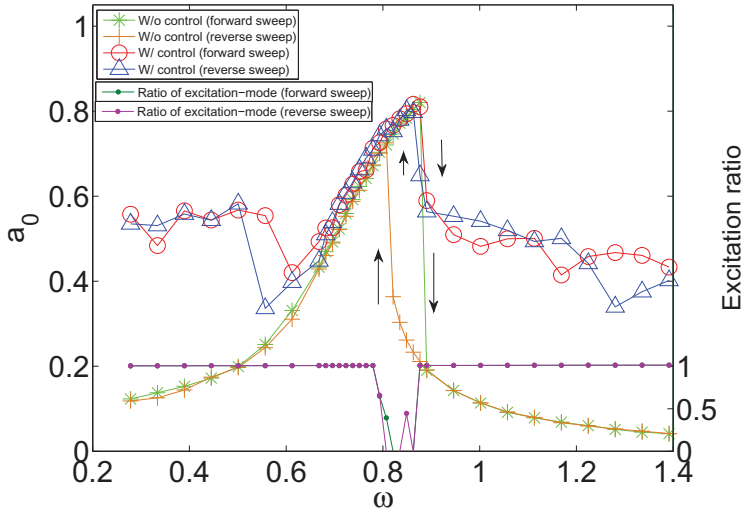


Figure 4. Experimental result.

horizontal shaking table and the relative displacement response of the harvester was measured by a laser displacement sensor mounted on the table. The shaking table was excited by a sinusoidal swept wave from 2 to 10 Hz with an acceleration amplitude fi ed at 0.3 G. The positive and negative resistances were set to 100 Ω and -75 Ω, respectively. The threshold value used in the switching control was set to 74 % of the full stroke.

Figure 4 shows the experimentally obtained resonance curve of displacement responses with and without switching control plotted in a dimensionless form. From the figure one can see that there is a hysteresis of the resonance curve in the case without control. This is because there are two stable solutions in this frequency band. In contrast, the resonance curve with control in the figur shows that the presented prototype harvester successfully destabilized the low energy solution, which provides the global stability to the highest-energy solution. The right axis of the plot is an excitation ratio, which is define as a duty ratio of negative resistance. The frequency band where the excitation ratio completely

vanishes is the band where the oscillator is ideally entrained into the high energy solution, while in other frequency band the load resistance is switched to negative intermittently to excite the oscillator. This suggests that the switching control should be activated only in the band of the entrainment to prevent undesirable loss of energy.

4. Conclusion

In this study, an experimental verificatio of a self-excitation control of a resonance-type vibration energy harvester with a Duffing-type nonlinear energy harvester which is designed to perform effectively in a wide frequency range is presented. The experimental results show that the prototype switching circuit between positive and negative load resistances and its control law as a function of the displacement amplitude have successfully destabilized the undesirable low energy solution and provided the global stability to the highest energy solution.

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