A broadband energy harvester using leaf springs and stoppers with response stabilization control

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Abstract. This paper presents the design, fabrication and experimental verification of a broadband vibration energy harvester having a nonlinear oscillator using leaf springs and stoppers. In the conventional vibration energy harvester having a linear oscillator, there is a trade-off relationship between the magnitude of the resonance peak and the resonance band. Since the resonance band is expanded by using the nonlinear oscillator, the harvester can more efficiently generate electric energy in a wider frequency band. In this study, we designed and fabricated a nonlinear vibration energy harvester with leaf springs and stoppers, and verified the frequency response characteristics and the power generation performance of the proposed harvester by sinusoidal sweep tests with the input acceleration amplitude of 0.2 G. The overall resonance bandwidth was approximately 33 Hz, which was over 75% of the linear natural frequency of 42 Hz. The response stabilization control successfully destabilized the coexisting low-energy solution, and activated only the high-energy response in the resonance band.

1. Introduction

Vibration energy harvesting is a technology for generating electricity from ambient vibration. Since the power generation is effectively performed by resonating a mechanical oscillator with the source vibration, there is a tradeoff between the maximum power performance and the bandwidth. When the resonance band is expanded by introducing a nonlinear oscillator, the harvester can more efficiently generate electricity in a wider frequency band [1, 2]. However, since such nonlinear oscillators may have high and low-energy stable solutions coexisting in the resonance band, a mechanism to keep the oscillator responding in the high-energy solution is required to maintain the power generation performance. In the previous study done by Masuda et al. [3], a response stabilization control in order to globally stabilize the high-energy solution was proposed, in which a circuit switching between a positive and a negative load resistances depending on the response amplitude of the oscillator was introduced to give the harvester self-excitation capability. In the study done by Sato et al. [4], this response stabilization control was implemented to an energy harvester with a magnetically sprung oscillator. But the resonance band was not wide enough.

In this paper, an electromagnetic broadband vibration energy harvester with a nonlinear oscillator consisting of leaf springs and stoppers is designed and fabricated. The resonance band and the power generation performance in the frequency domain are verified by sinusoidal sweep tests. The response stabilization control is then applied to show the wideband operation of the proposed energy harvester.
2. Energy harvester design

2.1. Nonlinear oscillator

The mechanical design of the proposed energy harvester is shown in figure 1. An oscillator mass block sprung by a pair of leaf springs was arranged inside a casing so that the mass block could translationally move in the vertical direction. The leaf spring made of stainless steel thin plate with a thickness of 0.1 mm was designed in the Ω-like shape as shown in figure 2. Both ends of the spring were fixed to the casing with epoxy adhesive. The Ω-like shape of the spring was chosen to allow a large deformation of the spring without a hardening effect. Four stoppers made of PLA resin were placed close to the leaf springs. Since the effective length of the leaf springs was shortened after contacting the stopper, a hardening effect was imparted to the oscillator.

For the electromagnetic induction, a magnetic circuit consisting of four Neodymium magnets and two yoke plate was implemented in the mass block as shown in figure 3. A stator coil fixed in a coil holder was inserted in the airgap of the magnetic circuit, so that the magnetic flux passing through the coil moved along with the mass block motion. In order to allow as much flux as possible to pass through the coil, and to keep the leakage flux as little as possible, the yoke plates were used as a part of the structural frame of the mass block as an improved design, which made the mass block frame stiff enough to make the airgap as small as possible. As a result, the electromechanical coupling factor (the ratio of the induced voltage to the mass velocity) was improved from the previous design [5] by almost 50%.

A prototype with the improved magnetic circuit was fabricated as shown in figure 4. The specifications of the prototype harvester are listed in table 1.

![Figure 1](image1.png)  
Figure 1. Design of the proposed harvester.

![Figure 2](image2.png)  
Figure 2. Leaf spring (unit: mm).

![Figure 3](image3.png)  
Figure 3. A-A’ cross section.

2.2. Response stabilization control

In general, a nonlinear oscillator can have multiple stable solutions in the resonance band. The response stabilization control proposed by Masuda et al. [3] is a control of switching the load resistance between positive and negative values according to the response magnitude in order to globally stabilize the highest-energy solution by destabilizing the lower-energy solutions. The equation of motion of the harvester with the response stabilization control is given by

\[
m\ddot{x}(t) + \left( c + \frac{\Phi^2(x(t))}{R(a) + R_G} \right) \dot{x}(t) + F(x(t)) = -mu_a \cos \omega t
\]

where \( m \) is the mass and \( c \) is the mechanical damping coefficient, \( x \) is the relative displacement of the mass and \( u_a \) is the amplitude of the input acceleration. The functions \( \Phi(x) \) and \( F(x) \) are the
Table 1. Parameter values.

| Description                        | Value [unit] |
|-----------------------------------|--------------|
| Oscillator mass                   | 8.6 [g]      |
| Stiffness of leaf spring          | 365.4 [N/m]  |
| Linear natural frequency          | 42 [Hz]      |
| Electromechanical coupling factor | 9.92 [V/s/m] |
| Internal resistance of coil       | 320 [Ω]      |

When the response amplitude of the oscillator is larger than a predetermined threshold, the induction coil is connected to the positive load resistance (generation mode). If the amplitude drops below the threshold, then the circuit switches to the negative load resistance which is realized by a negative impedance converter (NIC) circuit. When connected to the negative resistance, the total damping coefficient $c + \Phi^2(x)/\left(R(a) + R_G\right)$ becomes negative, so that the oscillator is excited and entrained into the highest-energy solution (excitation mode). For the better performance of the stabilization, the threshold value should be determined depending on the excitation level and frequency [6].

For the implementation of the response stabilization control, the displacements of the mass block and the harvester casing, and the acceleration of the casing were measured by laser displacement sensors and an accelerometer, respectively, and all the signals were fed to the microprocessor (mbed LPC1768) to perform the load resistance switching. In this study, the power to drive the NIC circuit, the sensors, and the microprocessor was supplied by an external power source, which is to be self-supplied in the future study.

3. Experimental verification

An experimental verification of the resonance band and the power generation performance of the proposed energy harvester was carried out. The casing of the harvester was fixed to a vertical shaker and sinusoidal sweep tests in a frequency range of [35 Hz, 85 Hz] were conducted with an input acceleration amplitude of 0.2 G$_{\text{rms}}$. The stoppers were placed with a distance of 0.5 mm from the leaf spring. The load resistance and the negative resistance were set to 6.5 kΩ and -470 Ω, respectively. The threshold value was predetermined depending on the input frequency so that the response could be entrained to the high-energy solution favorably.

Figures 5 and 6 show frequency responses of the displacement amplitude and the generated power obtained by the sweep test with and without the response stabilization control. From the upper figures, it is found that the linear natural frequency was 42 Hz, and the tip of the resonance peak was extended to 75 Hz. Consequently, the proposed energy harvester showed significantly large bandwidth of 33 Hz, which was 78.5 % of the linear natural frequency. The maximum generation power at the peak frequency was 1.2 mW. In the lower figures, the responses with the proposed control were plotted. The red circles in figure 5 (b) shows the threshold values. It is obvious that the response stabilization control successfully destabilized the low-energy solutions, and the response of the harvester was always maintained in the high-energy solution.
4. Conclusion
In this paper, a broadband vibration energy harvester with a nonlinear oscillator using leaf springs and stoppers was presented, and sinusoidal sweep tests were carried out to examine its frequency response characteristics and power generation performance. It was concluded that, in the sweep tests at 0.2 G_rms excitation, the overall resonance bandwidth was approximately 33 Hz, which was over 75% of the linear natural frequency. In addition, the response stabilization control successfully destabilized the coexisting low-energy solution, and activated only the high-energy response in the resonance band.

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