Toward self-powered nonlinear wideband vibration energy harvesting with high-energy response stabilization

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Abstract. This paper describes an effort to develop a nonlinear wideband vibration energy harvester with self-powered stabilization control of its high-energy response. In a Duffing-type nonlinear wideband energy harvester, a well-recognized difficulty of coexisting attractors arises so that the emergence of the response in the high-energy branch is not guaranteed because it depends on the initial conditions to which steady-state solutions the state is attracted. The response stabilization control technique introduces a negative resistance which returns the harvested power to the nonlinear resonator to destabilize the undesirable low-energy solution and make the high-energy solution globally stable. In this paper, the power balance of the response stabilization control under intermittent disturbances is first experimentally studied, and a charging circuit to self-power the negative impedance converter (NIC) in the control circuit is then developed. It is concluded that the energy consumed by the NIC can be retrieved by the energy harvesting in 100 seconds even in the worst case.

1. Introduction

In nonlinear Duffing-type energy harvesters, the resonance band can be widened while keeping the maximum power generation performance by introducing hardening (or softening) characteristics in the mechanical resonator which leads to a bent resonance peak in the frequency domain toward right (or left). A well-recognized difficulty of coexisting attractors then arises so that the emergence of the response in the high-energy branch is not guaranteed because it depends on the initial conditions to which steady-state solutions the state is attracted. Masuda et al. [1] proposed a response stabilization control by introducing a negative resistance which returned the harvested power to the mechanical resonator to destabilize the undesirable low-energy solution and make the high-energy solution globally stable. The earliest proof-of-concept implementation of the proposed control was reported by Sato et al. [2], and it was then applied to a nonlinear harvester using leaf springs and stoppers [3], that achieved the overall resonance bandwidth of approximately 30 Hz or larger, which was over 60 % of its linear natural frequency of 42 Hz.

In those implementations, however, the power necessary to operate the response stabilization control was supplied by an external power source, so that the power consumption by the control circuit is still a critical problem. To achieve a self-powered response stabilization control, the power to drive the negative impedance converter (NIC), the power to drive the switching circuit, and the power to operate the microprocessor have to be all provided by the harvested energy accumulated in the energy storage. In this paper, the NIC circuit is tried to be self-powered as a first step. To this end, the power balance of the NIC circuit during the response stabilization control activated by intermittent disturbances is first experimentally studied, then the response stabilization circuit with a self-powered NIC is presented.
2. Nonlinear vibration energy harvester with response stabilization control

2.1. Nonlinear vibration energy harvester with leaf springs and stoppers

Figure 1 shows the structural drawing and the outer appearance of the electromagnetic nonlinear vibration energy harvester used in this study. This is the one that Kato et al. developed [3], in which leaf springs with $\Omega$-like shape are used to suspend a mass block, and mechanical stoppers are introduced to give the resonator well-defined hardening nonlinearity with low mechanical loss. For the electromagnetic induction, a magnetic circuit consisting of Neodymium magnets and yoke plates is built in the mass block. A stator coil is inserted in the air gap of the magnetic circuit, so that the magnetic flux passing through the coil moved along with the mass block motion.

Figure 2 is the frequency response of the harvester for the base excitation of 0.2 G$_{\text{rms}}$, and the load resistance of 5.1 k$\Omega$. The overall bandwidth is approximately 30 Hz, and the maximum power output is approximately 1.8 mW. A hysteresis is clearly observed in the frequency band from 46.5 Hz to 70 Hz, in which the high- and low-energy steady-state responses coexist.

Figure 1. Nonlinear vibration energy harvester using leaf springs and stoppers.

Figure 2. Frequency response of harvester with leaf springs and stoppers.

2.2. Response stabilization

In general, a nonlinear resonator can have multiple stable steady-state solutions in the resonance band. The response stabilization control proposed by Masuda et al. [1] 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. When the response amplitude of the resonator 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 NIC circuit. When connected to the negative resistance, the total damping coefficient becomes negative, so that the resonator is actively 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 the excitation frequency [4].

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. These sensing instruments will be replaced by a built-in low power sensors in the future version. All the signals were fed to the microprocessor (mbed LPC1768) to perform the load resistance switching. At this moment, the power to drive the NIC circuit, the sensors, and the microprocessor was supplied by an external power source. The power source for the NIC circuit was ±20 V.

Figure 3 is the frequency response of the harvester with the response stabilization control for the base excitation of 0.2 G_{rms}, and the load resistance of 5.1 kΩ. The negative resistance value was set to -510 Ω. The threshold value was set in accordance with the excitation frequency as plotted in red solid line in figure 3 (a). From the plots, 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.

3. Self-powered NIC circuit

3.1. Energy consumption in NIC circuit

The goal of this study is to achieve the response stabilization control using a self-powered NIC circuit. Prior to the development of such a self-powered circuit, it was experimentally investigated how much energy was required by the NIC circuit when it was activated in response to impulsive disturbances.

Figure 4 shows a circuit diagram of the NIC. The impedance of the circuit at the input terminal is $z = (R_1R_3)/R_2$. The total power consumed by the resistances $R_1$, $R_2$, and $R_3$ is calculated as

$$P_{NIC} = \left( \frac{R_2}{R_3} + \frac{R_1}{R_2} + \frac{R_1}{R_3} \right) P_{out}$$  \hspace{1cm} (1)

where $P_{out}$ is the power output from the NIC supplied to the induction coil of the harvester. This equation means that it always requires extra power consumed by the resistances in the NIC in order to supply the excitation power to the harvester. For example, when the resistance values are all the same, the value in

![Figure 3](image-url)  \hspace{1cm} (a) Displacement amplitude response.

![Figure 3](image-url)  \hspace{1cm} (b) Harvested power.

**Figure 3.** Frequency response of harvester with leaf springs and stoppers with response stabilization.
the parentheses becomes three, so that the power three times as much as the power actually supplied to the harvester is required and lost as Joule heat. To reduce this extra power, equation (1) suggests that the resistance values on the negative feedback side ($R_2$ and $R_3$) should be much larger than the positive feedback resistance $R_1$, so that the second and third terms in parentheses are negligible. Furthermore, if the voltage division ratio on the negative feedback side is increased, the first term can also be brought close to zero. In the experiment described below, the resistance values of $R_1$, $R_2$, and $R_3$ were chosen as 510 $\Omega$, 10 $k\Omega$, and 10 $k\Omega$, respectively. Thus, the power consumption in the NIC resistances were almost same as the power provided to the harvester.

Next, an experiment was carried out to see how much energy was actually consumed in the NIC circuit when the response stabilization control performed. It would contain the energy supply to excite the harvester, the energy consumed in the NIC resistances, and the energy loss in the operational amplifier. The experiment was conducted as follows: first, the harvester was excited by a sinusoidal base acceleration of 0.2 G$_{\text{rms}}$ and 70 Hz, which corresponded to the maximum power point shown in figure 3 (b). Then, the stabilization control was turned on so that the harvester operated in the high-energy response. After it reached steady-state, impulsive disturbances were given to the mass block by touching by hand at random timing. The voltages and currents were measured to calculate: (a) the energy supplied to the induction coil from the NIC circuit to excite the harvester, (b) the energy consumed by the resistances in the NIC circuit, and (c) the energy loss in the operational amplifier by subtracting the sum of (a) and (b) from the energy supplied from the DC power source, during the excitation mode was activated. The whole procedure was repeated 20 times.

Figure 5 shows the results as a bar graph. The red bar (a) is the energy supplied to the harvester, the green (b) is the energy consumed by the resistances in the NIC circuit, and the blue (c) is the energy loss in the operational amplifier. As predicted, the values of (a) and (b) are almost equal. The energy loss in the operational amplifier (c) is dominant, so the reduction of the DC voltage may be effective to suppress this loss. The right axis shows the the energy consumption value divided by the average harvested power in this condition (1.8 mW) to see how many seconds is required to retrieve the consumed energy by harvesting energy. From this result, it is found that the energy consumption of the response stabilization control against a single disturbance can be retrieved by harvesting energy in an average of 20 seconds.

3.2. Response stabilization circuit with self-powered NIC

Based on those results, a charging circuit to provide power source to drive the NIC circuit was designed as illustrated in figure 6, based on a circuit known as a voltage quadrupler. This circuit can supply positive and negative DC voltages, which is twice the input maximum voltage of the harvester. The output capacitors C3 and C4 were connected to the operational amplifier to self-power the NIC circuit. To examine the performance of the response stabilization circuit with self-powered NIC, the harvester was first excited in the high-energy response with 70 Hz and 0.2 G$_{\text{rms}}$ base excitation until the capacitors...
C3 and C4 were fully charged. Then, impulsive disturbances were given to the mass block by touching by hand. The disturbances were applied five times. The first three were relatively light, and the last two were relatively strong. The capacitance value of the capacitors C3 and C4 used in the experiment was 22 mF. The temporal variation of the voltage of the capacitor C3 is shown in figure 7. The drops of the voltage correspond to the timing of the disturbances, and these drops were due to the energy consumption by the response stabilization control. From the plot, one can see that, for the light disturbances, the energy consumed by the response stabilization was retrieved in 10 seconds, and it took at most 80 seconds even if the disturbance level was strong.

4. Conclusion
In this paper, the response stabilization control to globally stabilize the high-energy response of nonlinear vibration energy harvesters has been experimentally studied in terms of energy consumption. The power balance of the NIC in the response stabilization circuit has been first investigated, then the response stabilization circuit with a self-powered NIC has been developed. It has been concluded that the energy consumed by the NIC can be retrieved by the energy harvesting in 100 seconds even in the worst case.

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