

# A Bistable Vibration Energy Harvester with Closed Magnetic Circuit

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**Abstract.** In this work, to increase magnetic flux passing through the electric coil in a bistable vibration energy harvester, the magnetic circuit is made closed by introducing two coil systems which have magnetic core in their axis holes. The magnetic resistance of the magnetic circuit, composed of silicon steel and thin air gaps, is suppressed to be small. The double well potential is realized from the spring force and nonlinear magnetic force between the magnets and the magnetic core. Two harvesters with opened and closed magnetic circuits are manufactured for comparison. It is also shown that the closed magnetic circuit can effectively improve the output power.

## 1. Introduction

Energy harvesting devices have been receiving much attentions as voltage source for low-powered wireless sensor nodes with autonomous operations [1]. The electromagnetic vibration energy harvester (VEH) transforms vibration energy into electrical energy through magnetic induction [2],[3]. Conventional VEHs produce electric power through linear spring-damper oscillation. Thus, maximum power is obtained at the resonant frequency and the output power drops as operating frequency goes far away from the resonance. In order to make effective energy harvesting from real-world vibrations, the operational bandwidth of VEHs should be broaden.

For the wideband VEHs, various approaches have been proposed [4]. The use of the bistable structure is one of the attractive approaches [5]. Bistable VEHs are characterized by a double-well potential. As for the bistable VEHs, the inertial mass of VEH transits between two equilibrium positions if the oscillator can overcome the potential barrier by the vibrations regardless of frequency. Hence, the bistable VEHs have a possibility to realize broadband operation. In fact, it has been shown that bistable VEHs can harvest electrical power under noise excitations [6]. Moreover, the magnetic flux passing through the coil in VEHs should be increased to improve power generation efficiency.

In this work, to increase magnetic flux in a bistable VEH, we make the magnetic circuit closed by introducing two coil systems which have magnetic core in their axis holes. The magnetic resistance of the magnetic circuit, composed of silicon steel sheets and thin air gaps, is suppressed to be small. The double well potential is realized from the spring force and nonlinear magnetic force between the magnets and the magnetic core. Two harvesters with opened and closed magnetic circuits are manufactured for comparison. It is also shown that the closed magnetic circuit can effectively improve the output power.

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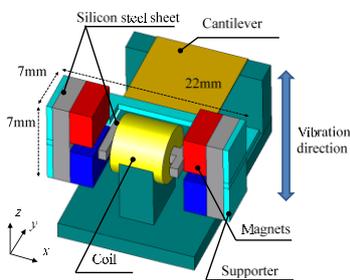
## 2. Bistable harvester with closed magnetic circuit

It is necessary to improve the operational bandwidth and the output power of VEH. The electromotive force induced in the coil is equal to the time derivative of the magnetic flux across the coil. The magnetic flux should be, therefore, increased to improve the output. Introduction of magnetic materials in the magnetic circuit allows us to increase the flux linkage with the coil. When introducing magnetic materials, attraction magnetic force, which is nonlinear with respect to displacement, is generated between magnets and magnetic materials. This nonlinearity would broaden the frequency bandwidth of the VEH. It is thus expected that appropriate magnetic circuit design leads to the improvements of both the bandwidth and the output power.

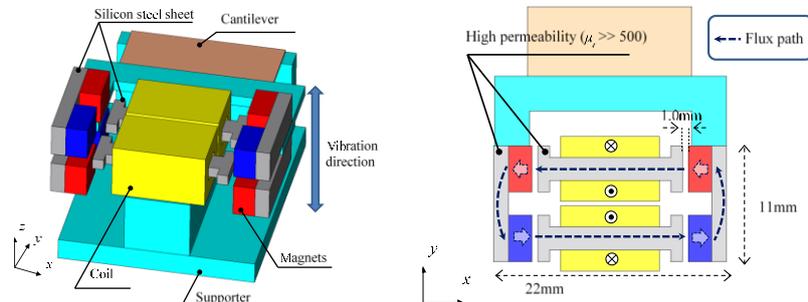
On the basis of the above mentioned insight, we have been developed a VEH harvester model using magnetic material [7, 8]. In this work, a harvester which has H-shaped magnetic core shown in figure 1 is considered. This model is here called H1-harvester. For the magnetic core in the axis hole of the coil bobbin, we employ the silicon steel sheets whose relative permeability is much higher than the space permeability. The magnetic flux is expected to be much larger in this VEH in comparison with the VEH whose magnetic core is made of Ferrite [7, 8]. It is therefore expected that the H1-harvester can improve the output power. However, the magnetic resistance is still large because the magnetic flux outside the coil has to pass the air region.

For this reason, another harvester with a closed magnetic circuit is presented, as shown in figure 2, called here H2-harvester. In this model, two H-shaped magnetic cores are introduced in two coils so as to form closed magnetic circuit, as shown in figure 2(b). It is thus expected that the flux linkage with the coils can effectively be increased in comparison with the H1-harvester.

In these two models, nonlinear attraction magnetic force is generated between the magnets and the magnetic cores. When carefully tuning the magnetic force and spring constant, the bistable potential is realized, as will be mentioned below. Thus, it is expected that introduction of the magnetic cores not only improve the efficiency but also broaden the bandwidth of the harvester.



**Figure 1.** H1-harvester model with opened magnetic circuit.



**Figure 2.** H2-harvester model with closed magnetic circuit.

We now consider the potential energy in the proposed harvesters. The potential energy,  $E$ , in the VEH is written by

$$E(z) = E_{\text{mag}}(z) + \frac{1}{2}kz^2, \quad (1)$$

where  $k$  is spring constant, and  $z$  is the relative displacement of the coil and magnets. Moreover,  $E_{\text{mag}}$  is magnetic energy which can be computed by the finite element method as follows:

$$E_{\text{mag}}(z) = \iiint_V E_m(z) dV, \quad (2)$$

where

$$E_m(z) = \begin{cases} \frac{\|\mathbf{B} - \mathbf{B}_r\|^2}{2\mu} & \text{magnet,} \\ \int_0^{\|\mathbf{B}\|} \|\mathbf{H}(b)\| db & \text{otherwise,} \end{cases} \quad (3)$$

and  $\mathbf{B}_r$  is remnant flux density in magnet. Note that  $E_m(z)$  is a function of  $z$  because flux distribution,  $\mathbf{B}$ , varies depending on  $z$ .

Figures 3 and 4 show the potential energy in the H1- and H2- harvesters, respectively, for three different values of  $k$ . It can be found that bistable potential structure can be realized when setting  $k$  to proper values. Moreover, when carefully tuning  $k$ , the potential barrier gets low, which makes it easy to transit the oscillator between two equilibriums. For example, in the H2-harvester, the appropriate value of  $k$  is about 1100N/m.

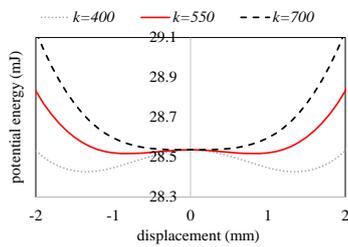


Figure 3. Potential energy in H1-harvester.

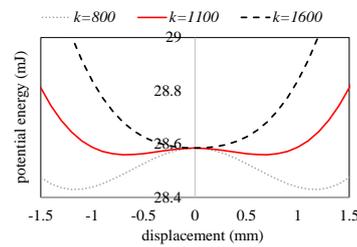


Figure 4. Potential energy in H2-harvester.

### 3. Experiments

The proposed harvesters was manufactured. Figure 5 shows the manufactured H2-harvester. The total mass of the oscillator (the magnets, core, and their keepers), effective spring constant of the cantilever,  $k$ , and the number of the turn in the coils are summarized in Table 1. To evaluate the performance with high potential barrier,  $k$  for the H1-harvester is set to relatively small.

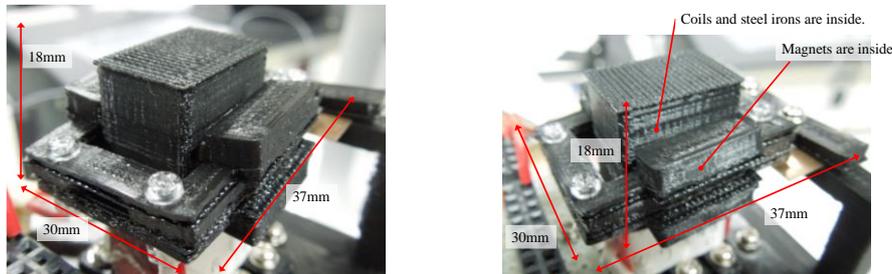


Figure 5. Manufactured H2-harvester.

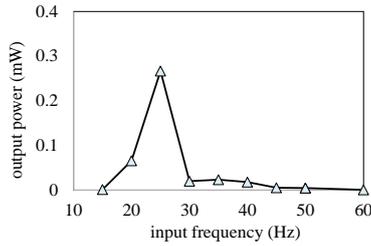
Table 1. Mechanical parameters in manufactured harvesters

	mass of oscillator (g)	effective spring constant of cantilever (N/m)	Number of turns in coil
H1-harvester	9.1	392	700
H2-harvester	8.0	1150	840

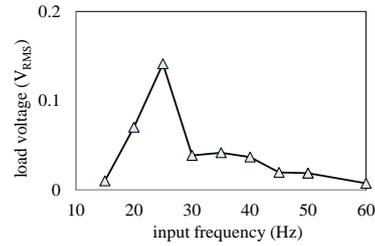
#### 3.1. Measurements

The output power against frequency for different frequencies was measured. Sinusoidal vibration was applied to the base of the proposed harvesters, and the acceleration level was fixed to about 1.0G at all the frequencies. A resistive load of  $75\Omega$  was connected to the coils, and the load voltage was measured by an oscilloscope.

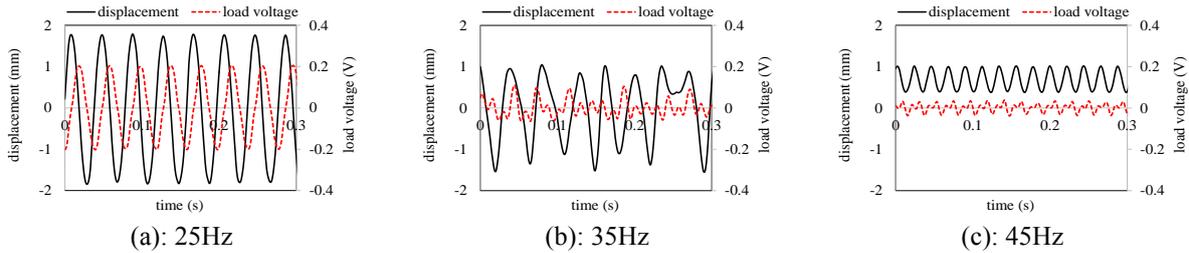
Figures 6 and 7 show the output power and load voltage, respectively, plotted against the input frequency in the H1-harvester. These figures show that the maximum is located at about 25Hz, and



**Figure 6.** Output power in H1-harvester.



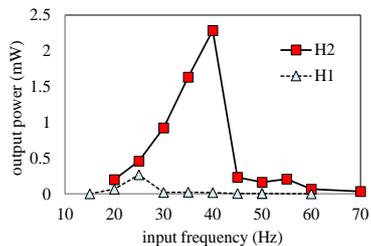
**Figure 7.** Load voltage in H1-harvester.



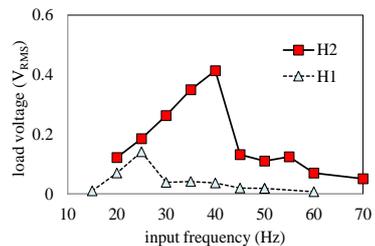
**Figure 8.** Time-variation of displacement and load voltage in H1-harvester.

around which the outputs drop. The time-variation of displacement and load voltage are shown in figure 8, from which it is found that H1-harvester has three distinct behaviour modes. These modes well correspond to the behaviour modes of bistable VEH: interwell, chaotic, and intrawell oscillations [5]. Thus, this result strongly suggests that the manufactured H1-harvester has a bistable property. Nevertheless, the bandwidth is not broaden. This would be due to the fact that the potential barrier in the manufactured H1-harvester is high when  $k$  is about 400, as shown in figure 3. High potential barrier makes it difficult to produce the interwell oscillation, as a result, the bandwidth of the bistable VEH is narrow.

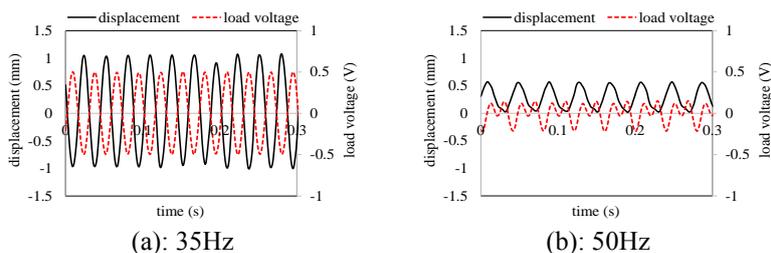
The output power and load voltage in the H2-harvester are shown in figures 9 and 10, respectively, which show that the output of the H2-harvester is much greater than that of the H1-harvester. Although efficiency of two harvesters is not simply compared because the numbers of turns in them are different, this result clearly indicates superiority of the superiority in the closed magnetic circuit. However, the H2-harvester again has a relatively narrow peak at about 40Hz. The time-variation of displacement and load voltage are shown in figure 11. At 35Hz, the amplitude of the oscillation is large. On the other hand, at 50Hz, the oscillation of the displacement is biased and its amplitude is



**Figure 9.** Output power in H2-harvester.



**Figure 10.** Load voltage in H2-harvester.



**Figure 11.** Time-variation of displacement and load voltage in H2-harvester.

much smaller than that at 35Hz. From these results, it can be said that the H2-harvester has two distinct behaviour modes depending on the input frequency. This fact suggests that the H2-harvester does not have a bistable property.

### 3.2. Discussions

Here, the reason why the H2-harvester does not have the bistable property is discussed. One of the considerable reason is due to the manufacturing error. As for bistable VEHS, the coil axis is aligned to the center of the magnet at the neutral position. The potential energy profiles for the misaligned coil are shown in figure 12, from which it is found that the H2-harvester does not have a double-well potential whereas H1-harvester has. Because the potential barrier in the H1-harvester is relatively high, bistable structure is maintained against the small misalignment. On the other hand, in the H2-harvester, the manufacturing results in disappearance of the double-well structure because of the low potential barrier. From these discussions, it can be concluded that bistable VEHS with low potential barrier can have broad bandwidth although it can easily lose the double-well potential due to manufacturing errors. In summary, the broadband bistable VEHS is not robust against the manufacturing errors.



**Figure 12.** Potential energy when misaligned (0.2mm).

## 4. Conclusions

This paper has presented the bistable harvester which has the closed magnetic circuit. The experimental results have suggested that the manufactured H1-harvester is bistable while H2-harvesters is not. It has also shown that the output power in the H2-harvester is much greater than that in the H1-harvester. The reason why the H2-harvester does not have double-well potential has been discussed.

For the future work, the bistable H2-type harvester will be developed by improving the manufacturing accuracy.

## 5. Acknowledgment

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