An Electromagnetic Vibration Energy Harvester With Strong Electro-mechanical Coupling

Hokkaido University: Takahiro Sato, Hajime Igarashi
1. Introduction

2. Vibration energy harvester with magnetic core

3. Measurement

4. Conclusion
If we can use low-power sensor ICs *without battery*, various new WSN systems will be realized!

...e.g., motioning the “health” of bridges and tunnels.

- Vibration is generated from the traffic on bridges.
- **Vibration energy harvester** is the device to produce the power from vibration.
- If we can harvest the small electric power form this vibration, the sensor ICs can work without any batteries.
Electromagnetic Vibration Energy Harvester

Electromagnetic vibration energy harvester (VEH) transforms vibration energy to electric energy through magnetic induction.

- When ambient vibration is applied to base (coil), the cantilever is oscillated.
- As a result, electromotive force is induced in the coil.
Electromagnetic Vibration Energy Harvester

- **Electromagnetic vibration energy harvester (VEH)** transforms vibration energy to electric energy through magnetic induction.

- Conventional VEHs produce the electrical energy through linear spring-damper oscillations.

- The output power is generated only around the natural frequencies of VEHs.

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**Diagram:**
- **Magnets**
- **Cantilever beam**
- **Coil**
- **Ambient vibration**

**Equation:**
- Mass on cantilever: \( m \)
- Effective stiffness: \( k \)
- Effective damping: \( c_m \)

**Graph:**
- Frequency (Hz) vs. Power (μW)
In the real-world, vibration has wide frequency spectrum. The operation bandwidth of VEH must be improved.

For real-world application...

- Higher output
  - In case of zigbee, about 2mW is necessary.
- Broader bandwidth
  - VEHs must be produce the power from wider frequency range.

We propose a new harvester by introducing magnetic materials
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For Higher output,

- The electromotive force is equal to the time derivative of the magnetic flux across the coil $\Phi$.

$$V = N \frac{D\Phi}{Dt} = N \frac{D}{Dt} \int_S \mathbf{B} \cdot i_s dS$$

- Electro-mechanical coupling can be increased by forming appropriate magnetic circuits.

< with magnetic circuit and two magnets pairs >  < without magnetic circuit >
Concepts for improvement of performance

➢ For Higher output,
  ○ appropriate magnetic circuits should be designed.

[Diagram showing magnetic circuits with and without pairs of magnets]

➢ For wider bandwidth,
  ○ nonlinear phenomena is used.

[Graph showing voltage, displacement, and frequency with and without magnetic circuits]

entrainment, hysteresis, chaotic, etc.....
Our previous work

- Based on the mentioned concepts, we have developed a harvester with nonlinear oscillations.\(^1,2\)

- A soft-magnetic composite core (SMC core) is introduced to form a magnetic circuit.

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Our previous work

- The harvester has wide bandwidth.
- The oscillator has a complicated (chaotic) motion.

Although the harvester has a wide bandwidth, the maximum voltage is under $0.2V_{\text{RMS}}$.

To connect rectifier circuits to the harvester, over $0.2V_{\text{RMS}}$ is necessary.

In this work, we enhance this harvester model to increase the output and bandwidth.
Nonlinear VEH with magnetic cores

- A harvester with silicon steel sheets is presented.

- The silicon steel sheets form a closed magnetic circuit to increase the flux linkage with the coils.

- As a result, electro-mechanical coupling will be increased.
Nonlinear VEH with magnetic cores

- Attraction magnetic force is generated between magnets and the cores.
- The magnetic force is nonlinear with respect to displacement, which gives rise to nonlinearity.

By forming magnetic circuits,
- higher output
- wider bandwidth

would be simultaneously realized.
Electromotive force

- The effect of the introduction of the steel iron sheet is evaluated by FEM.
- It is clear that the silicon steel sheets can effectively increase electromotive force.

<Electromotive force when magnets moving at 0.15m/s.>
We now consider potential energy of VEH, \( E \).

\[
E(X) = E_{\text{mag}}(X) + \frac{1}{2} kX^2,
\]

where \( E_{\text{mag}} \) is the magnetic energy, \( k \) is the spring constant. It can be found that the potential profile depends on \( k \).

![Potential energy graph]

\(<\text{Potential energy}>\)
Potential energy

\[ E(X) \approx AX^2 \iff F = -ax \]

- When \( k \) is large, the VEH system would be near to linear.
- When setting proper \( k \), **bistable potential structure**\(^*\) is realized.
  - As for the bistable VEHs, the inertial mass of VEH transits between two potential wells if the oscillator can overcome the potential barrier by the vibrations **regardless of frequency**.
  - It has been shown that bistable VEHs can harvest electrical power under noise excitations.

behavior of bistable harvester

- Bistable harvester has three behavior modes

**<mode1>**
Transit two wells regularly.

**<mode2>**
Transit two wells irregularly.

**<mode3>**
Trapped one well.

interwell oscillation
(In general, mode2 is chaotic)

intrawell oscillation
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The proposed harvester was manufactured.
The output power was measured.

Fig. 4. Manufactured Harvester.
Experiments

- Sinusoidal vibration is applied to the harvester.

- Load voltage is measured by oscilloscope.

- A resistive load, 460Ω, is connected to the coil.

- The input acceleration is fixed to 1.0G for all the frequencies.
Experiments
Experimental results: $k=2000$

- The maximum output power is obtained at 60Hz.
- The maximum voltage is about 0.7V, which is sufficiently higher than the threshold of diodes which are included in the rectifiers connected to the harvester.
- The frequency characteristic is well similar to the linear oscillation.

Fig. 1. Load voltage

Fig. 2. Output power
Experimental results: $k=1000$

- The maximum output power is obtained at 40Hz.
- The output is increased with frequency, then drops at about 45Hz.

**Fig. 3.** Load voltage

**Fig. 4.** Output power
As expected, when $k=2000$, the frequency-response is seemed to be linear.

When $k=1000$, the operational bandwidth is not effectively improved.

Fig. 5. Output power
Discussion 1: when $k = 2000$

- In linear system, the resonant frequency is given by $\omega_n = \sqrt{\frac{k}{m}}$

- When $k = 2000$, the natural frequency is about 90Hz.
- However, the measured natural frequency is 60Hz.

![Fig. 5. Output power](image)

Original resonant point: 90Hz
Effective spring constant when \( k=2000 \)

- The total force acting on the harvester when \( k=2000 \) is shown in Fig. 6.
- The initial gradient of the total force is about 900N/m, which can be assumed to effective spring constant.
- In case of \( k=900 \), the resonant point is 60Hz.

\[
\frac{dF}{dx} \equiv k_{eff} \approx 900 \text{N/m}
\]

Fig. 6. effective total force when \( k=2000 \)
Discussion: behavior modes when $k=1000$

- From the potential energy, when $k=1000$, the system has bistable property, by which the operational bandwidth is improved.
- However, the bandwidth of the harvester is not improved.
- The time-variations of displacement and voltage is shown in Fig. 7, which shows that the harvester has two behavior modes.

![Fig. 7 Time-variations of displacement and voltage.](image)

(a): 35Hz

(b): 50Hz
Discussion 2: behavior modes when $k=1000$

- **ideal bistable structure**

- **manufactured harvester**

  - As mentioned before, the bistable harvester has three behavior modes.
  - However, the manufactured harvester has two modes.
Experimental results

- The reason why the measured output does not agree with the analysis results would be due to the manufacturing error.
- Bistable VEH with low potential barrier easily loses the double-well potential due to manufacturing errors.
1. Introduction

2. Bistable harvester with magnetic core

3. Simulation and Measurement

4. Conclusion
Conclusion

- For high output and wider bandwidth, a harvester with silicon iron sheets has been presented.
- The proposed harvester has the closed magnetic circuit which is formed by the silicon iron sheets.
- When $k$ is large, the frequency response is almost linear.
- When $k$ is appropriately small, the harvester has bistable property in the ideal case. It has suggested that the bistable property is disappeared due to manufacturing error.

Future works

- Precise harvester will be manufactured.
- A new harvester model which is robust against manufacturing errors will be considered.