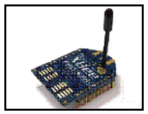
# An Electromagnetic Vibration Energy Harvester With Strong Electro-mechanical Coupling

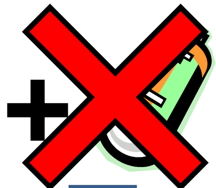

Hokkaido University: ○Takahiro Sato, Hajime Igarashi

1. **Introduction**
2. Vibration energy harvester with magnetic core
3. Measurement
4. Conclusion

# Background: What is vibration energy harvester ?

Low-power electronic devices for wireless sensing

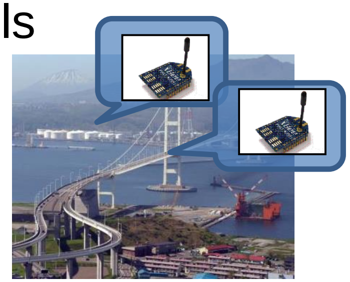




Zigbee, RFIF, etc,...

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

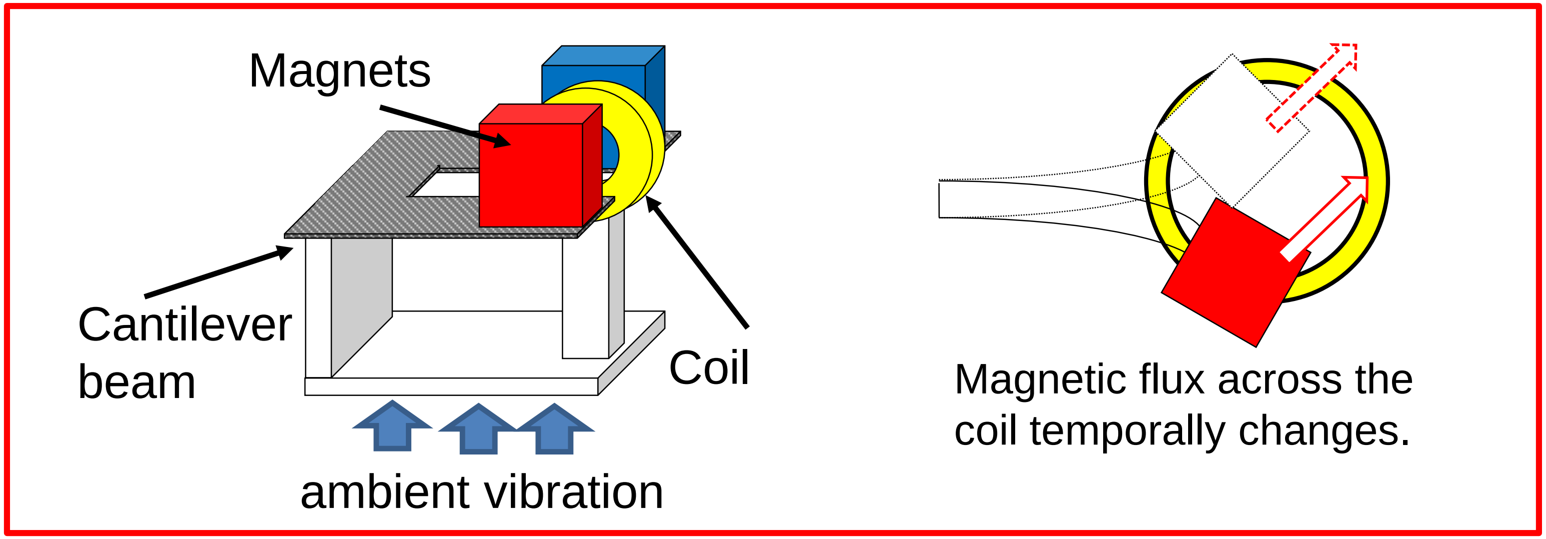


## Vibration energy harvester

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

# Electromagnetic Vibration Energy Harvester

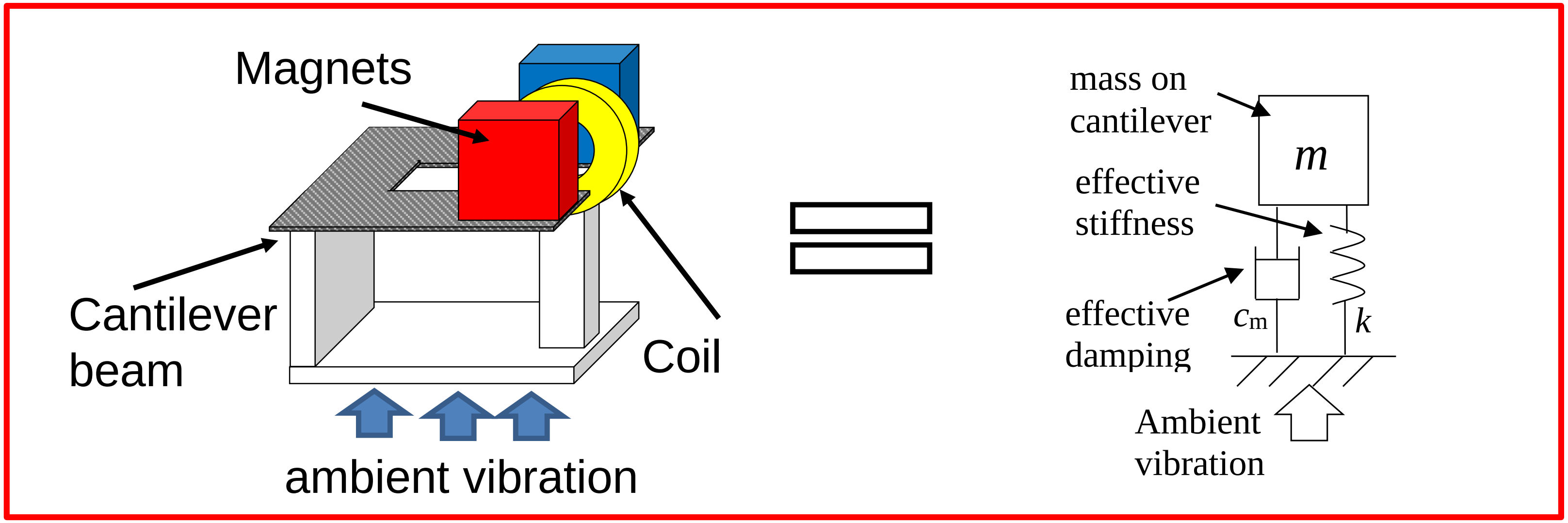
- **Electromagnetic vibration energy harvester (VEH)** transforms vibration energy to electric energy through magnetic induction.



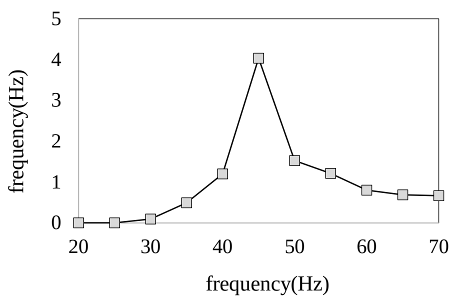

- When ambient vibration is applied to base (coil), the cantilever is oscillated.
- As a result, electromotive force is induced in the coil.

# 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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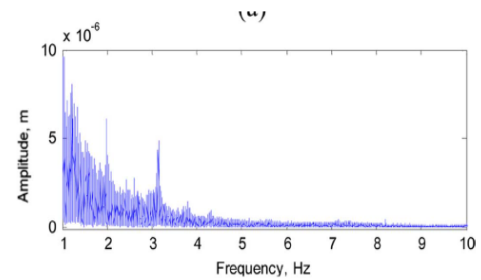
# Electromagnetic Vibration Energy Harvester

- 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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1. Introduction

2. **Vibration energy harvester with magnetic core**

3. Measurement

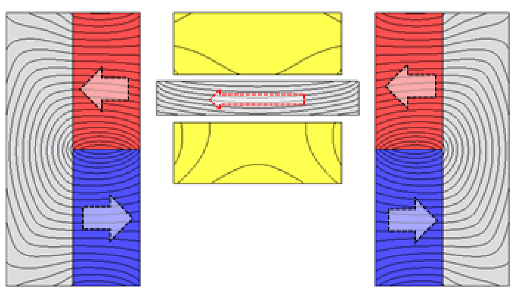
4. Conclusion

## ➢ For Higher output,

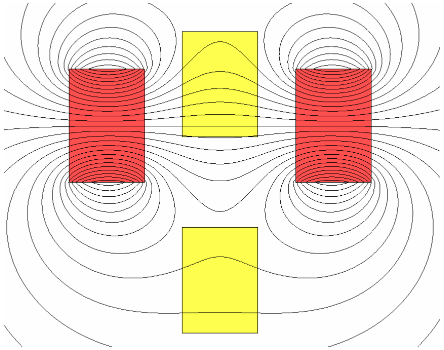
- The electromotive force is equal to the time derivative of the magnetic flux across the coil Φ.

$$V = N\frac{\mathrm{D}\Phi}{\mathrm{D}t} = N\frac{\mathrm{D}}{\mathrm{D}t}\iint_S \boldsymbol{B}\cdot\boldsymbol{i}_s dS$$

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



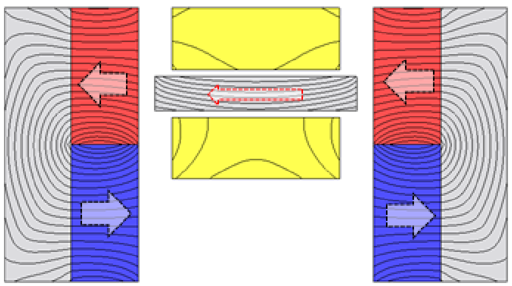
<with magnetic circuit and two magnets pairs>

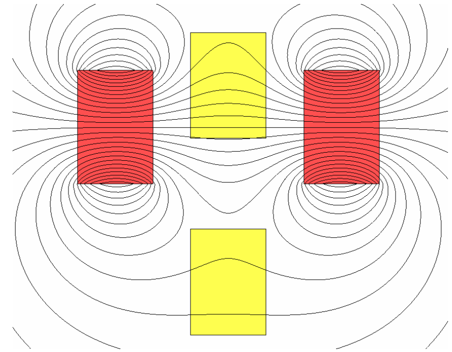


< without magnetic circuit >

# Concepts for improvement of performance

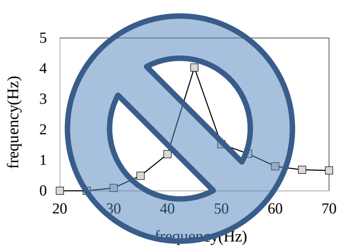
- **For Higher output,**
  - appropriate magnetic circuits should be designed.



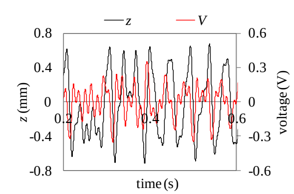


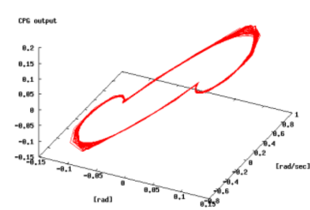
<with magnetic circuit and two magnets pairs> < without magnetic circuit >

- **For wider bandwidth,**
  - nonlinear phenomena is used.




entrainment,
hysteresis,
chaotic,
etc.....

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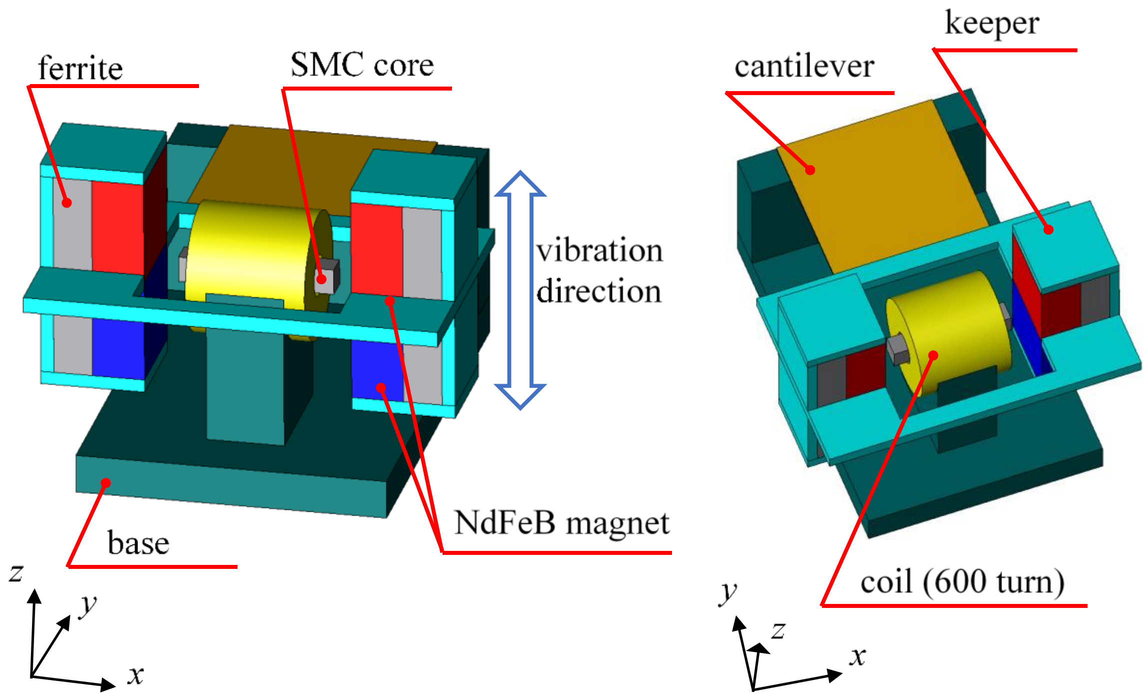
# Our previous work

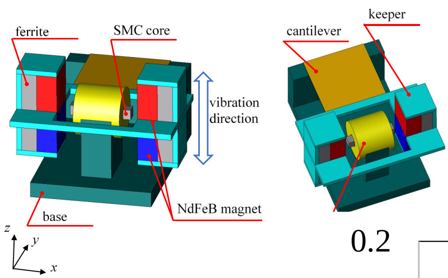
- Based on the mentioned concepts, we have developed a harvester with nonlinear oscillations.[1,2]

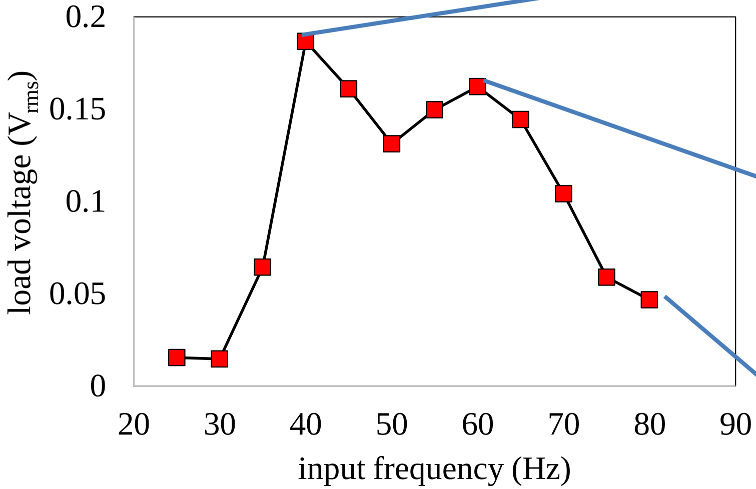


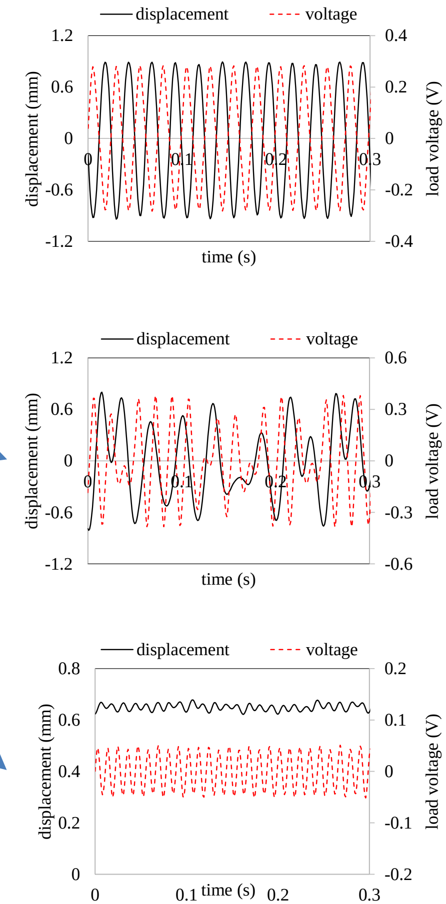

- A soft-magnetic composite core (SMC core) is introduced to form a magneticc circuit.

[1]: T. Sato, H. Igarashi, "A New Wideband Electromagnetic Vibration Energy Harvester with Chaotic Oscillation", Proc. of PowerMEMS2013, pp. 622-626, 2013.
[2]: T.Sato, H. Igarashi, "A Chaotic Vibration Energy Harvester Using Magnetic Material," submitted to Smart. Mater. Struct.

# Our previous work



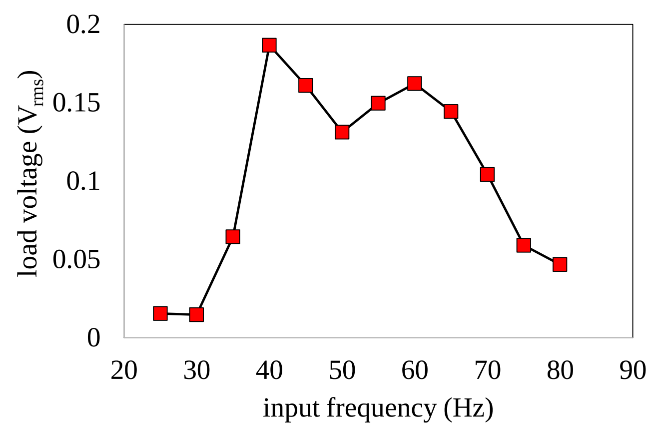



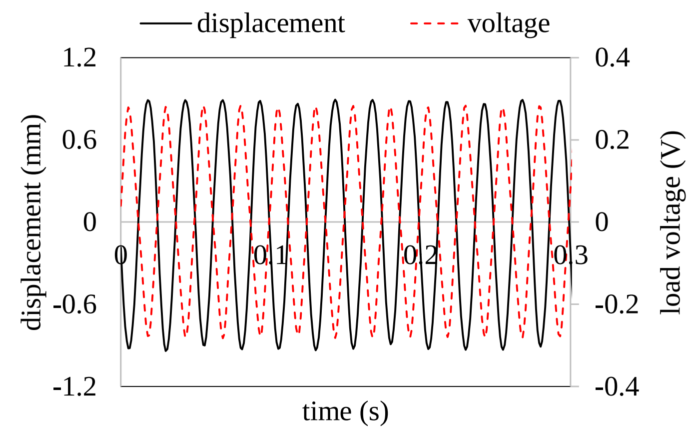

<Output power >

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


[1]: T. Sato, H. Igarashi, “A New Wideband Electromagnetic Vibration Energy Harvester with Chaotic Oscillation”, Proc. of PowerMEMS2013, pp. 622-626, 2013.
[2]: T.Sato, H. Igarashi, “A Chaotic Vibration Energy Harvester Using Magnetic Material,” submitted to Smart. Mater. Struct.

# Our previous work



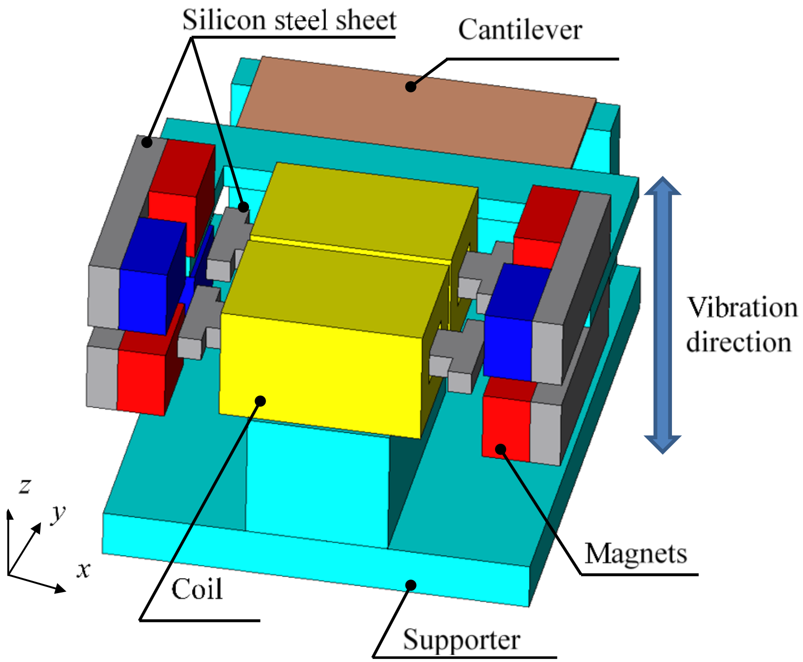



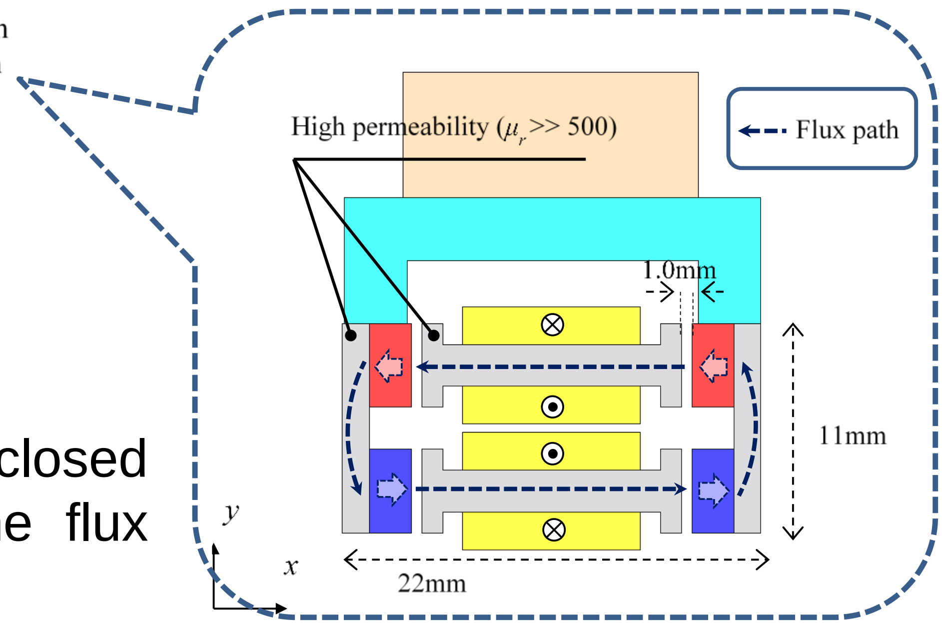

- Although the harvester has a wide bandwidth, the maximum voltage is under $0.2V_{RMS}$.
- To connect rectifier circuits to the harvester, over $0.2V_{RMS}$ is necessary.

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.

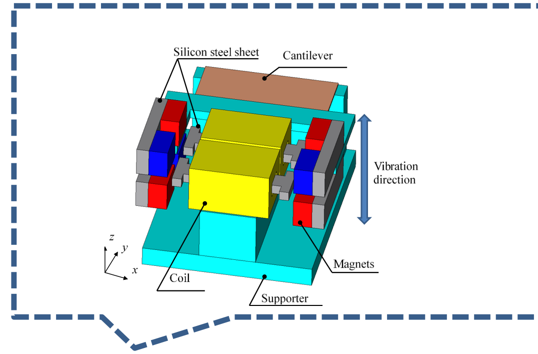


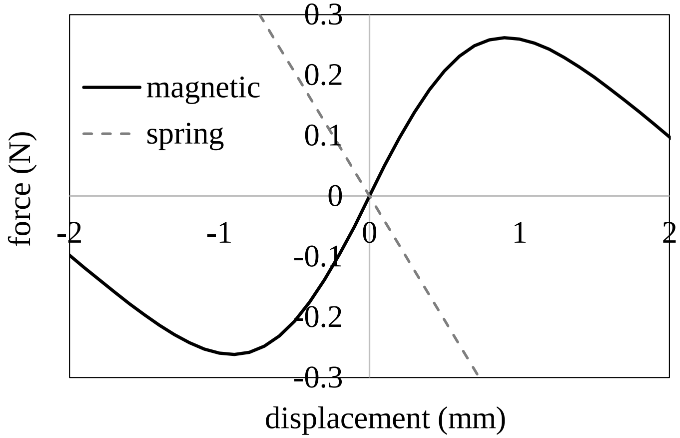




- The silicon steel sheets form a closed magnetic circuit to increase the flux linkage with the coils.
- As a result, electro-mechanical coupling will be increased.

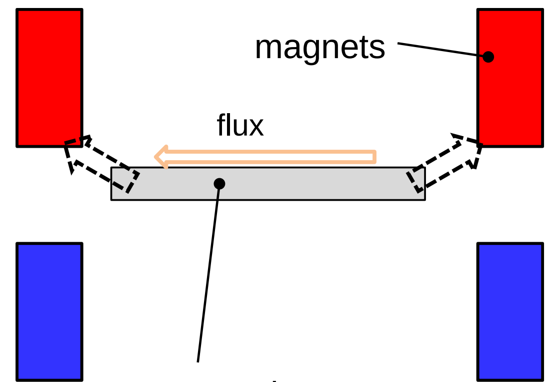
# Nonlinear VEH with magnetic cores

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




＜Magnetic and spring forces＞



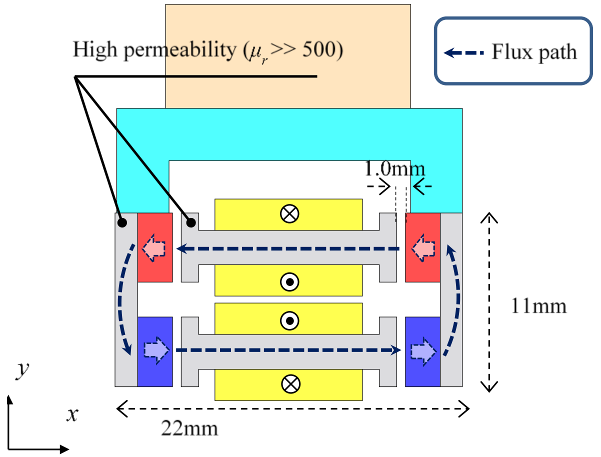

By forming magnetic circuits,

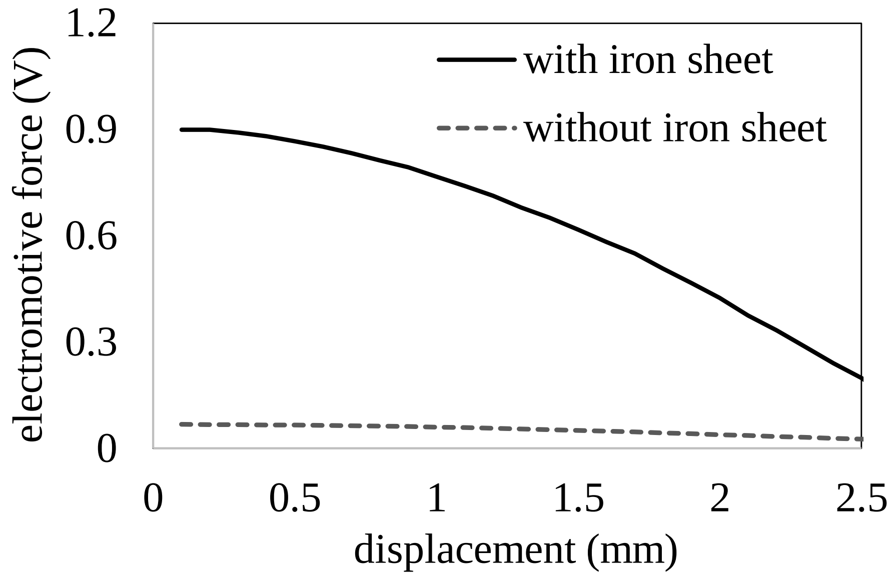
- **higher output**
- **wider bandwidth**

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.＞

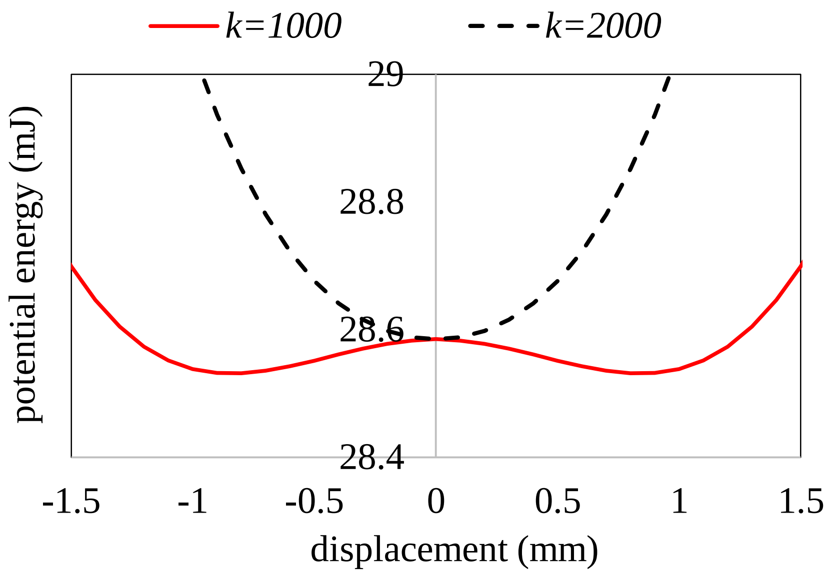
# Potential energy

- We now consider potential energy of VEH, $E$.

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

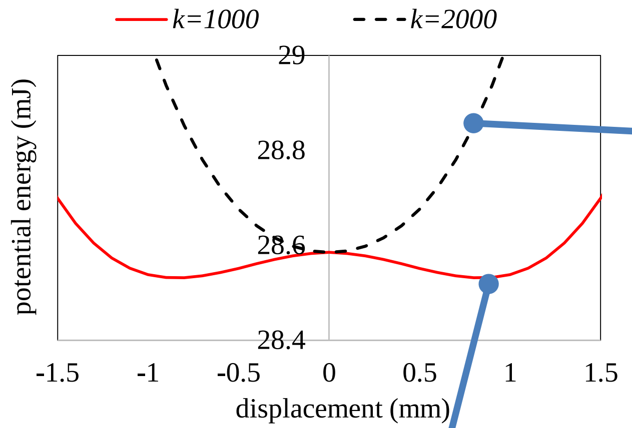
$E_{mag}$: magnetic energy
$k$: spring constant

- It can be found that the potential profile depends on by $k$.




＜Potential energy＞

# Potential energy




$$E(X) \approx AX^2 \Leftrightarrow F = -ax$$

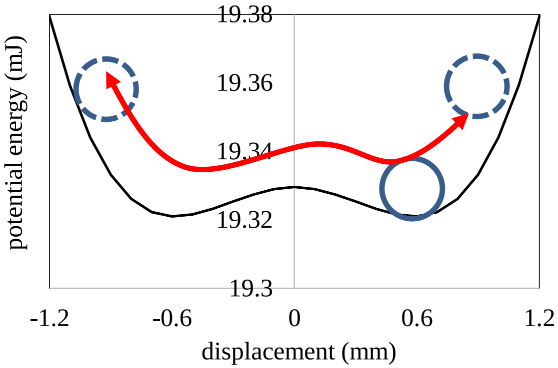
- When $k$ is large, the VEH system would be near to linear.

- 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.

[*]: R. L. Harne, K. W. Wang, 2013, A review of the recent research on vibration energy harvesting via bistable systems, Smart. Mater. Struct., vol. 22, no. 2, 023001.

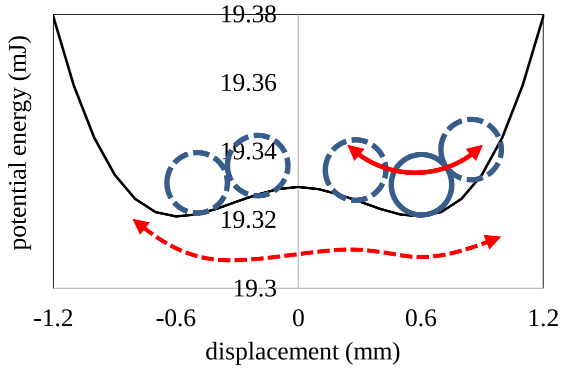
# behavior of bistable harvester

- Bistable harvester has three behavior modes



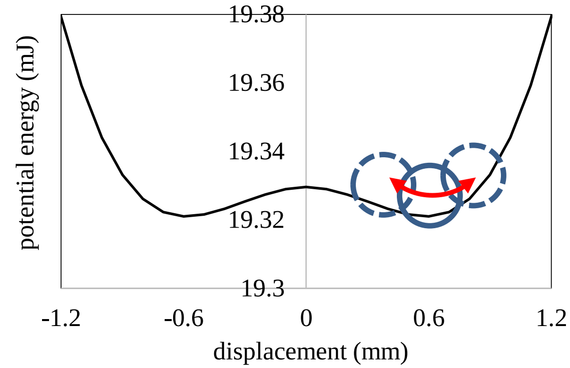

＜mode1＞

Transit two wells regularly.



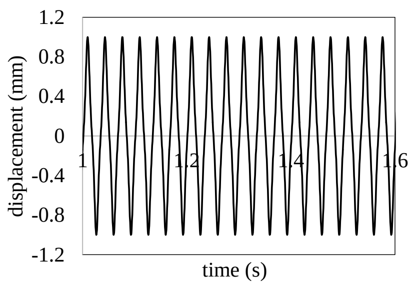

＜mode2＞

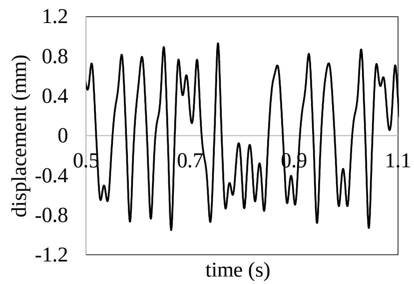
Transit two wells irregularly.

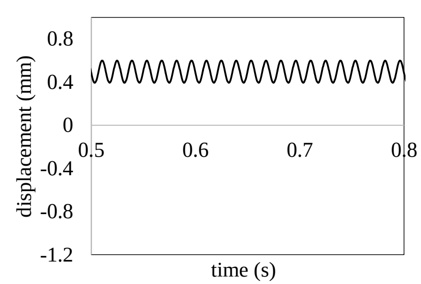



＜mode3＞

Trapped one well.




interwell oscilaltion

(In general, mode2 is chaotic)

intrawell oscillation

1. Introduction
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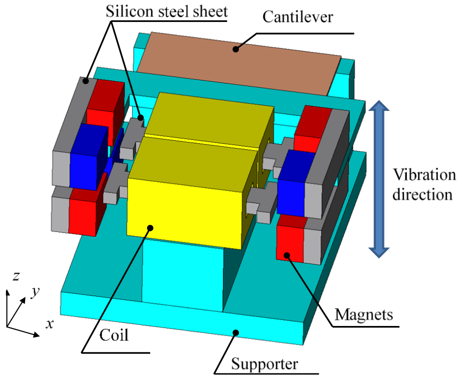
3. **Measurement**
4. Conclusion

# Experiments

- The proposed harvester was manufactured.
- The output power was measured.



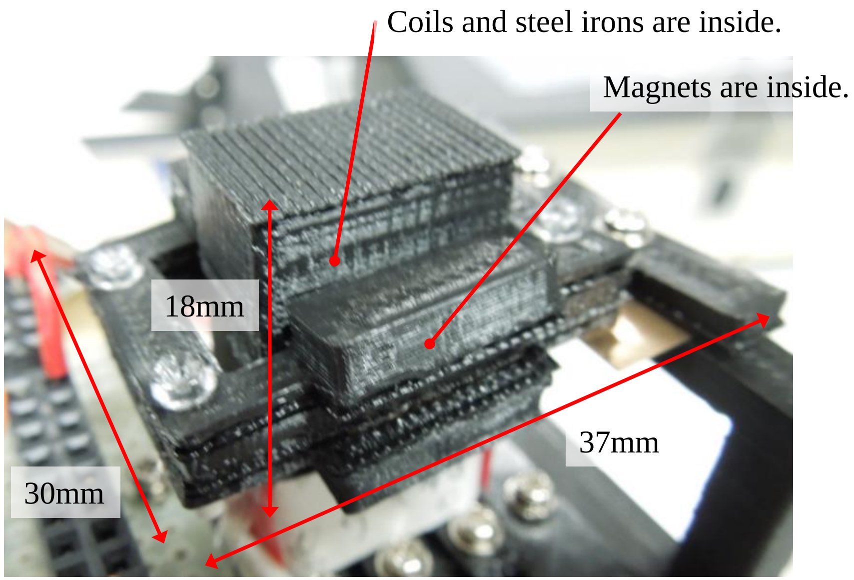




Fig. 4. Manufactured Harvester.

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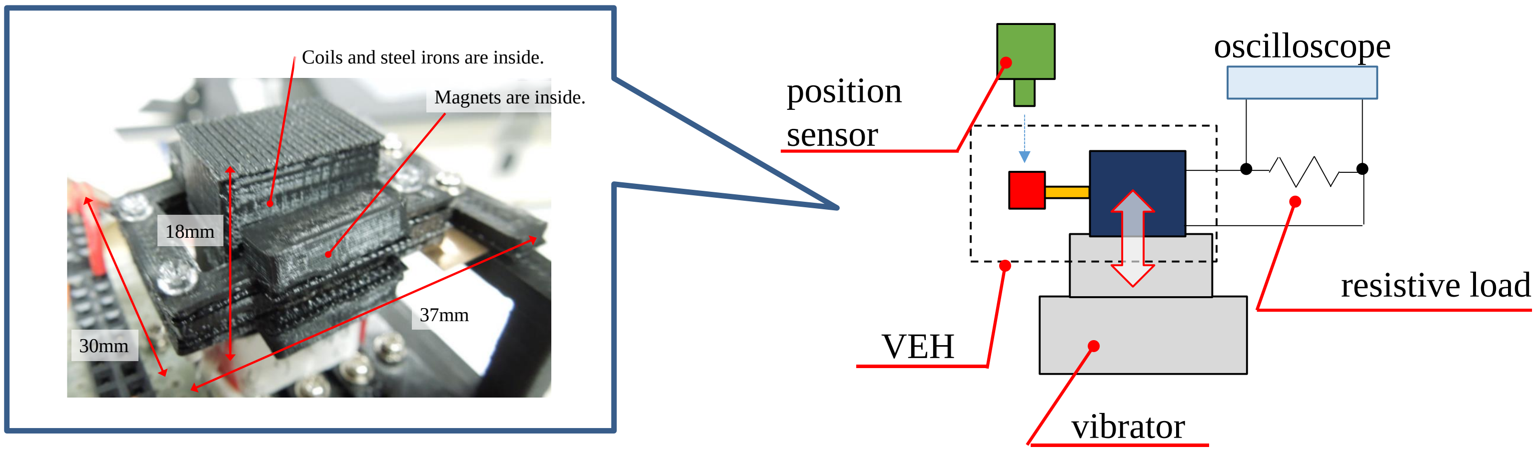
# Experiments

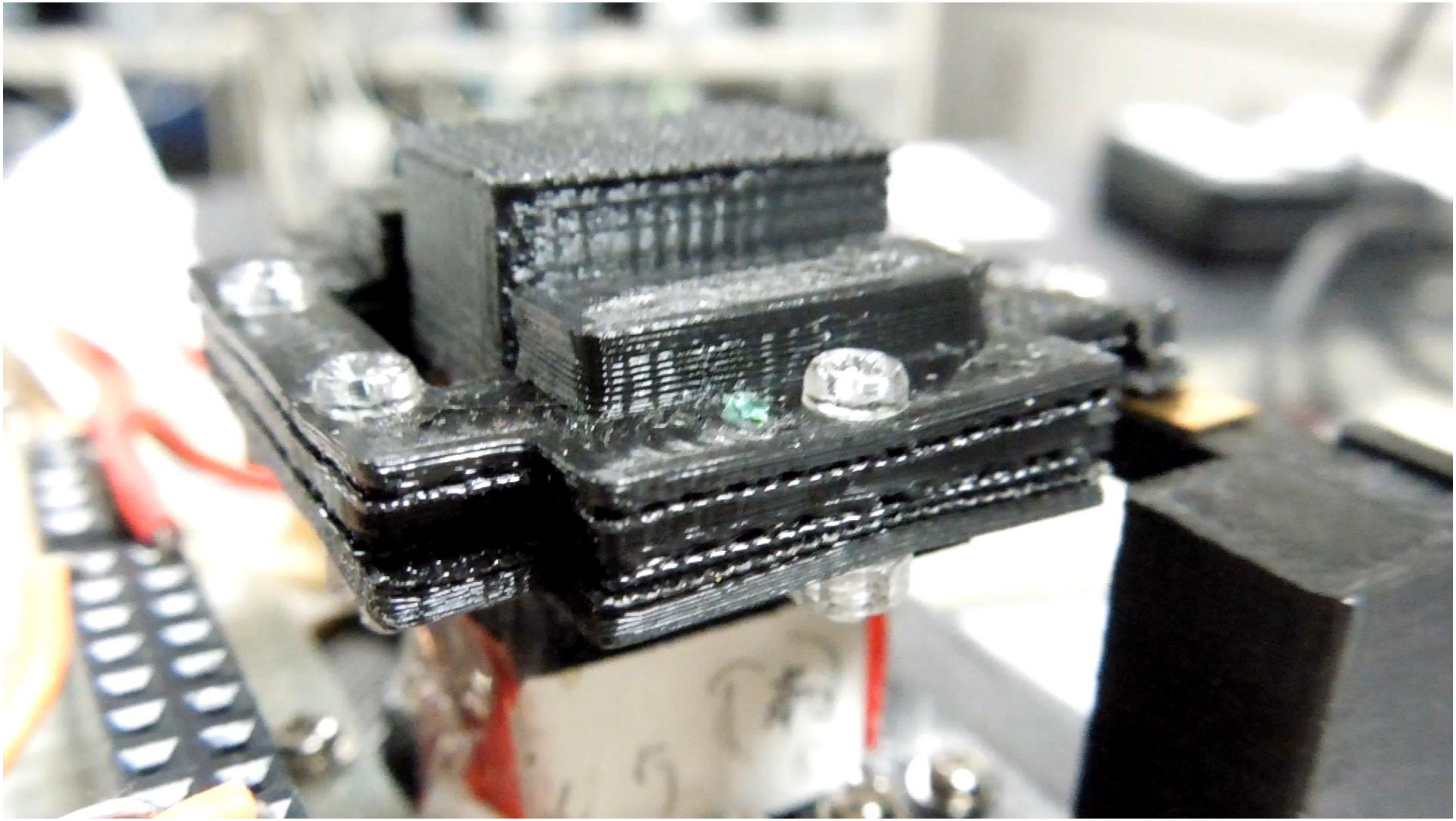
- Sinusoidal vibration is applied to the harvester.




- Load voltage is measured by oscilloscope.

- Aresistive 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.

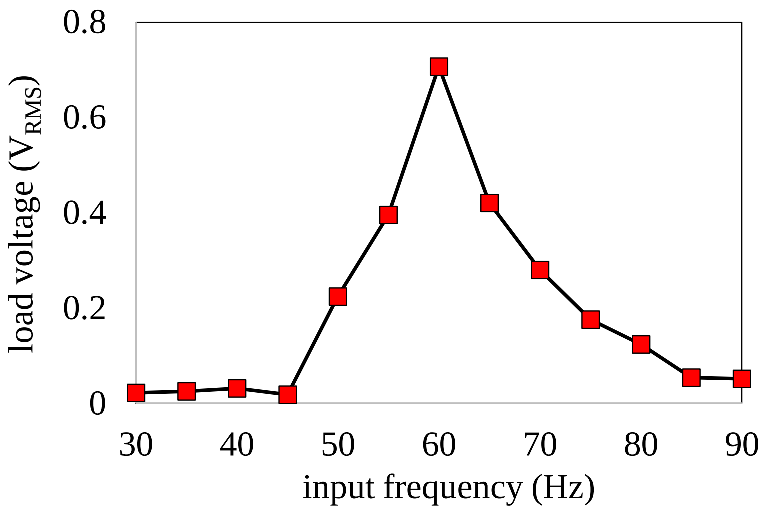



Fig. 1. Load voltage

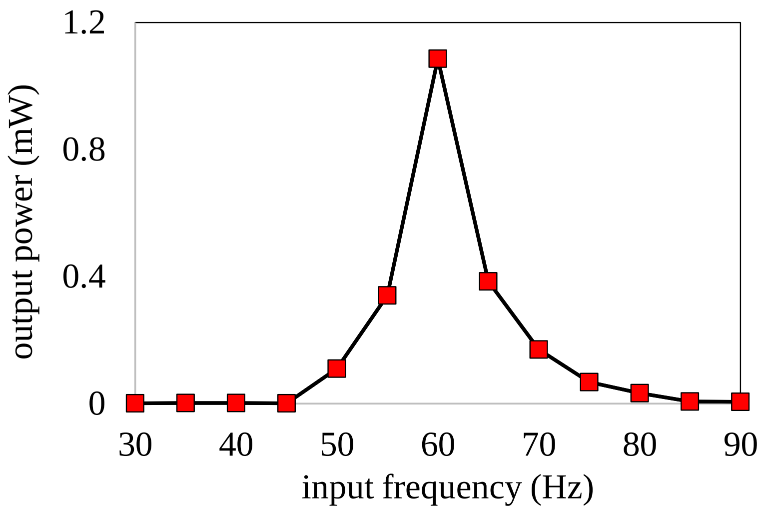



Fig. 2. Output power

# Experimental results: *k*=1000

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

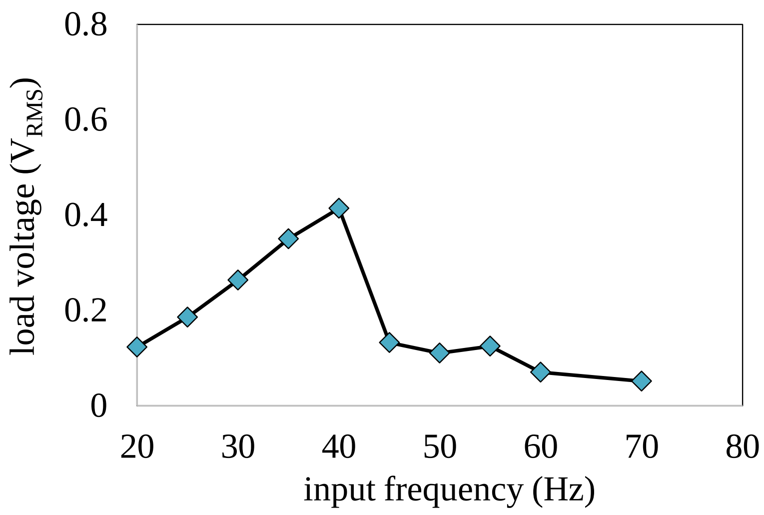



Fig. 3. Load voltage

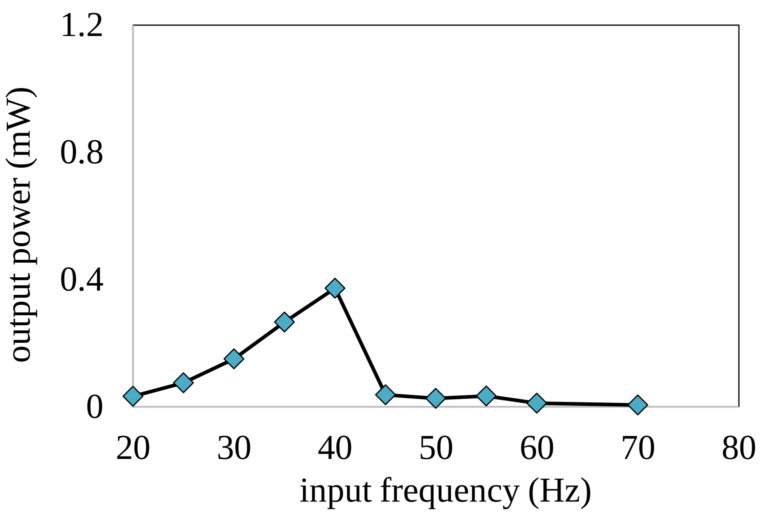
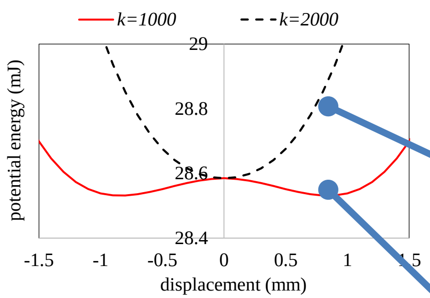



Fig. 4. Output power

# Experimental results

- As expected, when *k*=2000, the frequency-response is seemed to be linear.
- When *k*=1000, the operational bandwidth is not effectively improved.



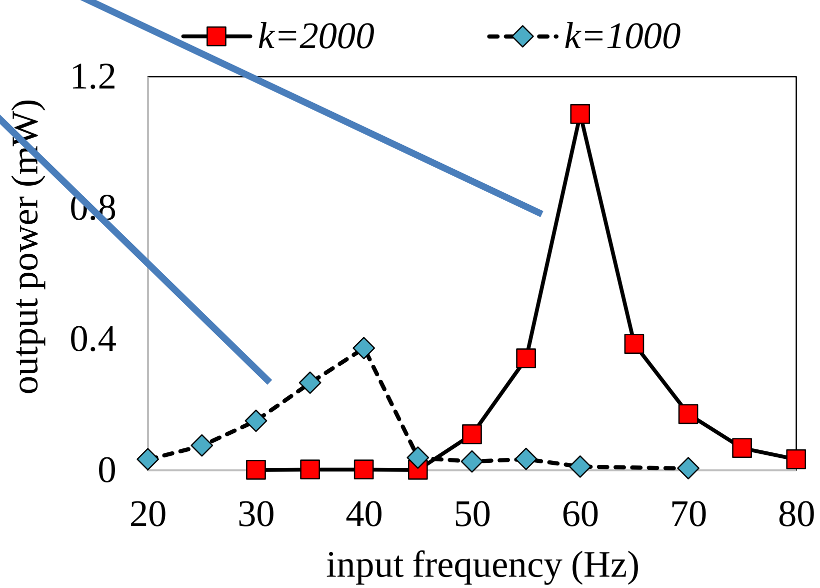




Fig. 5. Output power

# Discussion1: 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.

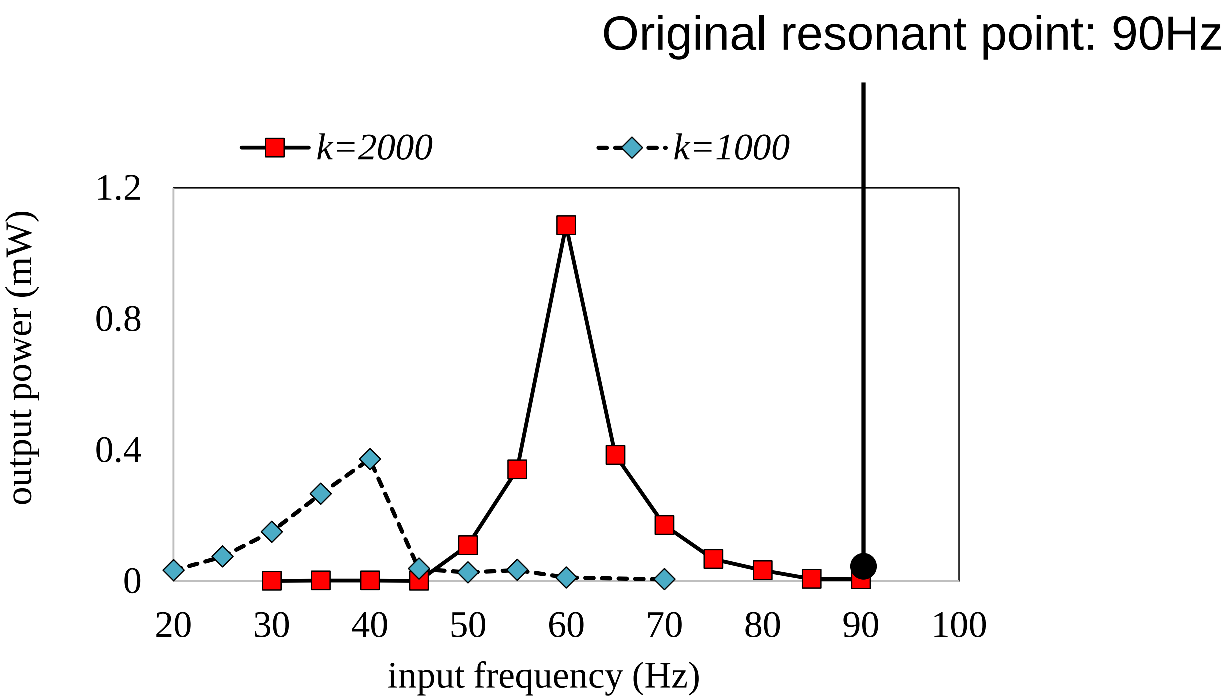



Fig. 5. Output power

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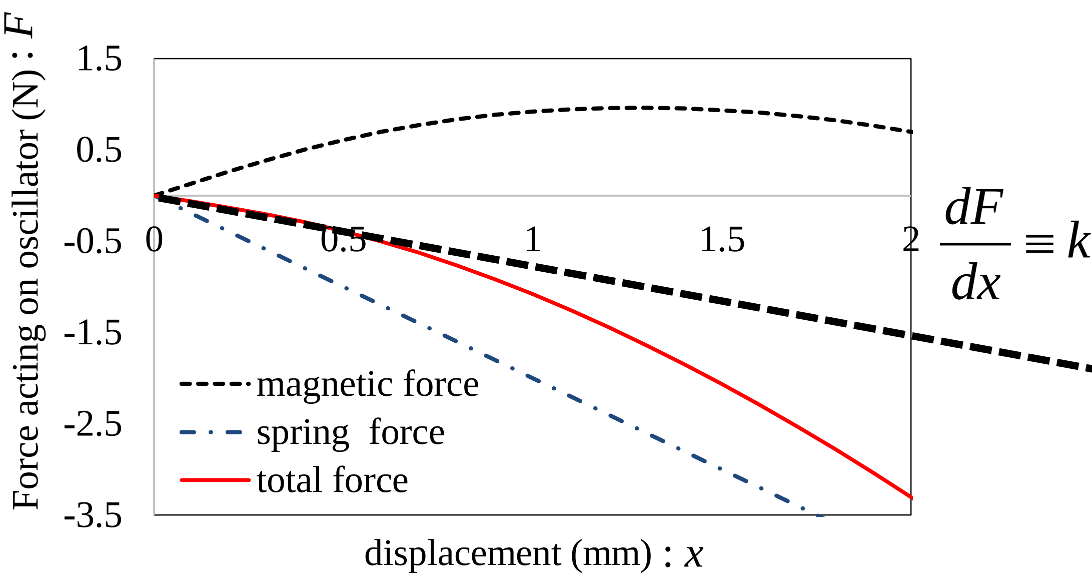
# Effective spring constant when $k$=2000

- 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.

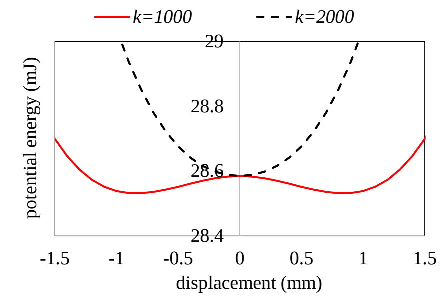


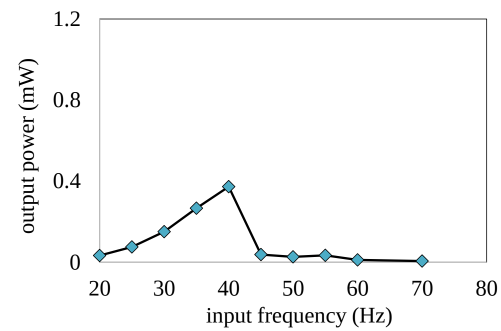

$$\frac{dF}{dx} \equiv k_{eff} \approx 900\mathrm{N/m}$$

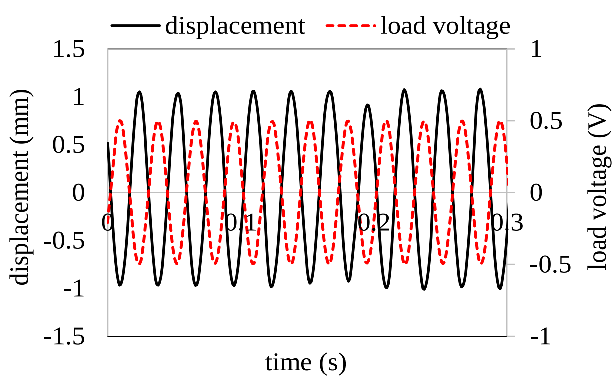
Fig. 6. effective total force when $k$=2000

# Discussion2: behavior modes when *k*=1000

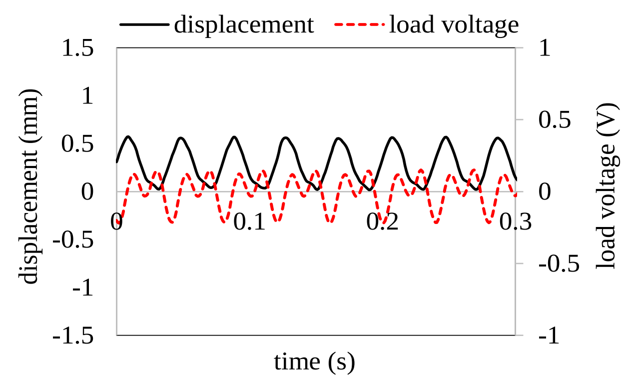
- From the potential energy, when *k*=1000, the system has bistable property, by which the operational bandwidth is improved.
- However, the bandwidth of the harvester is not improved.
- The time-variations of displacement and voltage is shown in Fig. 7, which shows that the harvester has two behavior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




(a): 35Hz




(b): 50Hz

Fig. 7 Time-variations of displacement and voltage.

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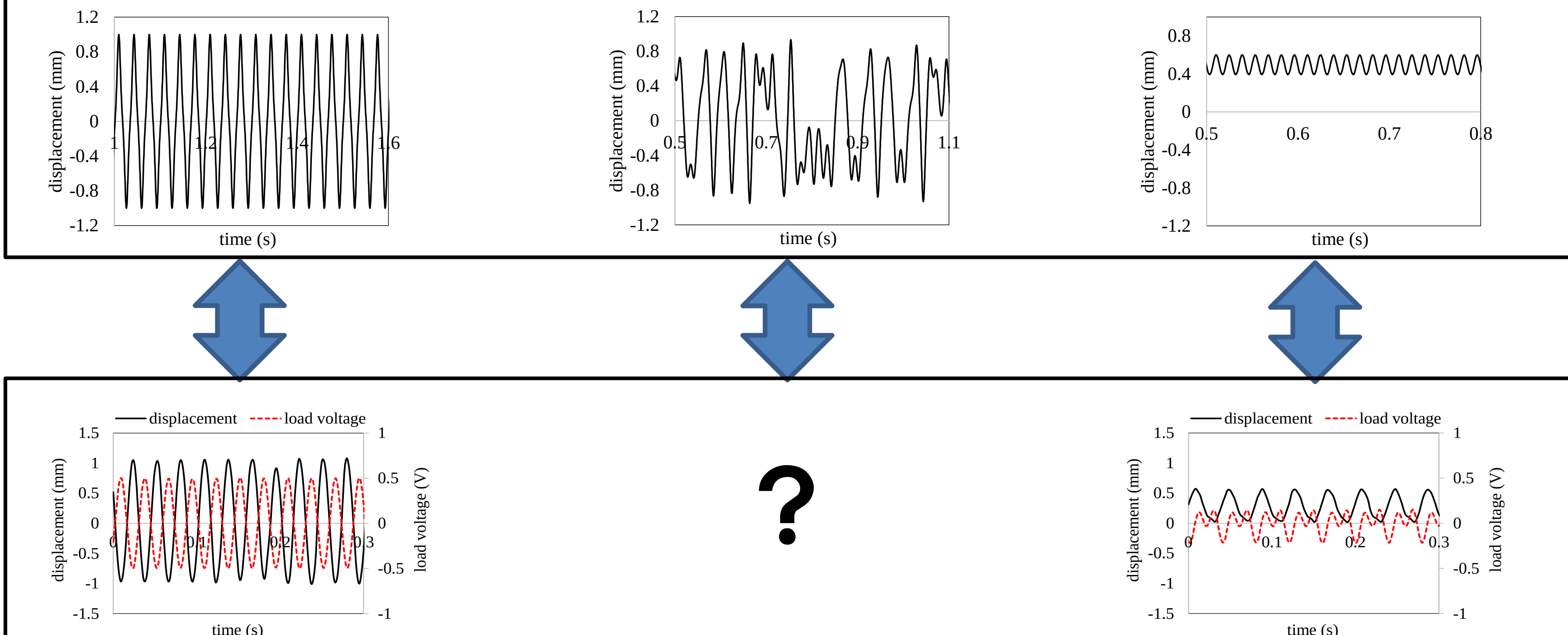
- ideal bistable structure

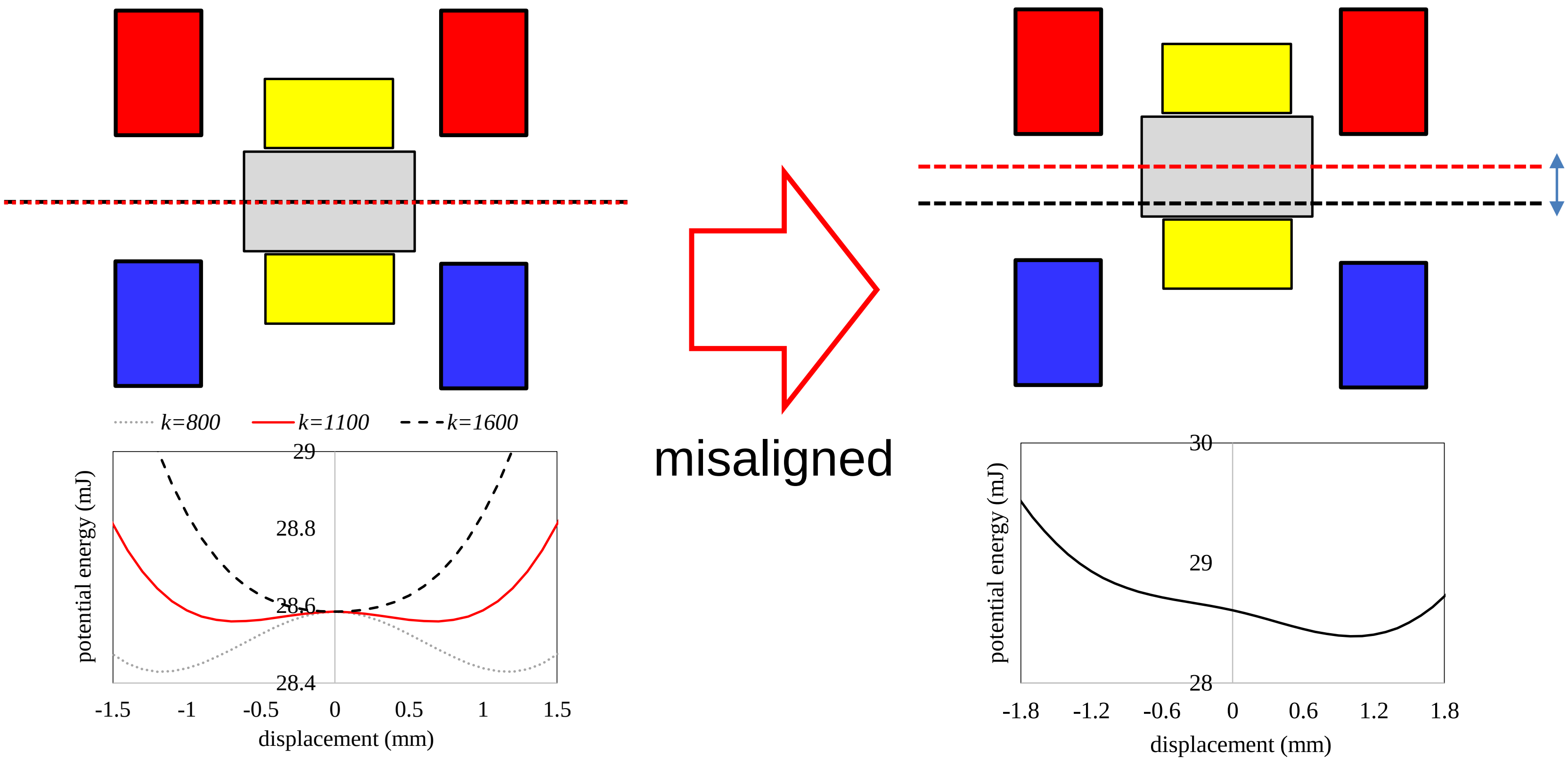



- manufactured harvester

- 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 looses the double-well potential due to manufacturing errors.

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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.