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A Hybrid Piezoelectric and Electromagnetic Energy Harvesting Device

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ABSTRACT

For all the ambient energy sources, mechanical vibration energy attracted most interests from researchers. There are two major mechanisms, electromagnetic and piezoelectric [1, 2], to convert the ambient vibration mechanical energy into useful electrical energy. To combine multiple sources for harvesting more available energy including combine piezoelectric and electromagnetic mechanisms to further increase the harvesting power output from mechanical vibration are already proposed before [3]. In this study, we will extend this idea to reuse the coils in generating power and also as the inductors required for synchronized switching techniques which can boost the piezoelectric power output. [4,5,6] For a piezoelectric generator based on a cantilever beam structure, a proof mass at the free end of the beam is usually applied to reduce the resonant frequency of the structure. A magnet can be used instead of a useless mass, and the coils can be fixed on the fixture of cantilever beam on the top of the magnet without increasing the overall size. [3] It is possible to reuse the inductance of the coil generators in the synchronous switching setup. We will first focus on the improvement of the harvesting power and emphasize that the combined device permits to harvest more power than the two separated devices and then proposed a mechanism for the coils reusing. The modeling and verification on this conceptual design will be detailed in this paper.

Keywords: power harvesting, piezoelectric generator, electromagnetic generator

1. INTRODUCTION

The wireless devices are improved in several aspects: their size shrunk and their power consumption decreased. In the mean time, we also hope the embedded power sources to get improved in the same factor. For now, most wireless devices are powered by batteries, and the improvement on the battery capacity and size are far lag behind the advancement of electronics. To get rid of the requirement of batteries, there are a lot of efforts done in energy harvesting to scavenging energy from ambient environment. For all the ambient energy sources, mechanical vibration energy attracted most interests from researchers. There are two major mechanisms, electromagnetic and piezoelectric [1, 2], to convert the ambient vibration mechanical energy into useful electrical energy. To combine multiple sources for harvesting more available energy including combine piezoelectric and electromagnetic mechanisms to further increase the harvesting power output from mechanical vibration are also proposed before [3]. In this study, we will extend this idea to reuse the coils in generating power and also as the inductors required for synchronized switching techniques which can boost the piezoelectric power output. [4,5,6]

The principle of the *electromagnetic generator* is based on induction with a magnet moving in a coil, which induces current flows in the coil loops. The *piezoelectric generator* uses the properties of piezoelectric elements: the deformation of the piezoelectric elements induces a voltage at its ends. The theoretical energy density of piezoelectric mechanism is higher than electromagnetic mechanism. However, most popular piezoelectric generator is cantilever structure, while the electromagnetic generator is actually simple coils. It is possible to combine them in a single package without increasing the overall size, but the generated powers are also sum of the two types of generators.

Considering a piezoelectric generator based on a cantilever beam structure, a proof mass at the free end of the beam is usually applied to reduce the resonant frequency of the structure. A magnet can be used instead of a useless mass, and the coils can be fixed on the fixture of cantilever beam on the top of the magnet without increasing the overall size. [3] The synchronous switching techniques have been successful to boost the power output of piezoelectric generators. However, no matter SSHI [4, 5] or charge extraction [6] all required an inductor in the switching loop. It is possible to reuse the inductance of the coil generators in the synchronous switching setup. In this study, we will proposed some configuration and circuit topology which can reuse the inductance of coils in synchronized switching techniques while still generating powers at the same time. We will s first focus on the improvement of the harvesting power and emphasize that the combined device permits to harvest more power than the two separated devices. Then, modeling on this conceptual design will be detailed studied in this paper.

2. PIEZOELECTRIC POWER HARVESTING DEVICE

The piezoelectric device consists of a cantilever beam, on which piezoelectric patches are fixed. A tip mass is added at the free end of the beam, to lower the resonance frequency and to increase the stress on the piezoelectric patches.

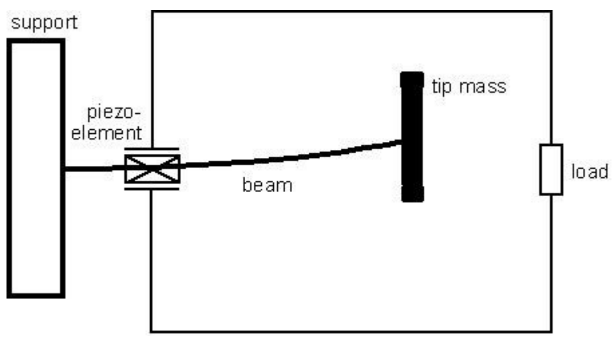


Figure 1. Schematic of a cantilever type piezoelectric energy haverster setup.

2-1. Modeling

Near the resonance frequency, if the displacement stay small enough to keep a linear movement, the piezoelectric structure can be modelized as a simple uniaxial system {mass+piezo+stiffness+damping}.

The piezoelectric equations (1) and (2) link the electrical and the mechanical variables. In these equations, F_{pz} is the equivalent force of the tip of the beam on the piezoelectric patches, u represents the displacement of the beam tip, V_{pz} and I_{pz} are the output voltage and current. K_{pze} is the equivalent stiffness of the piezoelectric element seen by the beam tip, when it is short-circuited. C_{pz} is the clamped capacitance of the piezoelectric element and is the equivalent force factor due to the material properties and the position on the beam.

$$F_{pz}=\tilde{K}_{pze}u+\tilde{\alpha}V_{pz} \tag{1}$$
$$I_{pz}=\tilde{\alpha}\dot{u}-C_{pz}\dot{V}_{pz} \tag{2}$$

The mechanical balance equation is given by the equation (3), where m is the tip mass, K_s the stiffness of the beam, d the damping and u the tip displacement. F is driving force of the vibration on the tip mass; we assume it is a sinusoidal force.

$$m\ddot{u}=F-\tilde{K}_{pze}u-\tilde{\alpha}V_{pz}-K_s u-d\dot{u} \tag{3}$$

At first, we don't take under consideration the rectifier and a possible synchronous switching device. For a resistive load R_{pz}, the electrical equation is:

$$V_{pz}=R_{pz}I_{pz} \tag{4}$$

These equations can be express in the following system:

$$\begin{pmatrix}\dot{V}_{pz}\\ \dot{u}\\ \ddot{u}\end{pmatrix}=\begin{pmatrix}\frac{-1}{C_{pz}R_{pz}} & 0 & \frac{\tilde{\alpha}}{C_{pz}}\\ 0 & 0 & 1\\ \frac{-\tilde{\alpha}}{m} & \frac{-(\tilde{K}_{pze}+K_s)}{m} & \frac{-d}{m}\end{pmatrix}\begin{pmatrix}V_{pz}\\ u\\ \dot{u}\end{pmatrix}+\begin{pmatrix}0\\ 0\\ \hat{F}\sin(2\pi f t)\end{pmatrix} \tag{5}$$

2-2. Optimization of the harvested power

The purpose of this section is to find the parameters to optimize the output power. It is possible to focus on three aspect to optimize the device.

2-2-1. Driving frequency

The mechanical device has a resonance frequency, linked to the global stiffness and mass of the system (equation 8). We assume that the vibration is sinusoidal, at the resonance frequency.

$$f_{respz}=\frac{1}{2\pi}\sqrt{\frac{\tilde{K}_{pze}+K_s}{m}} \tag{8}$$

Moreover, it is interesting to work at the resonance frequency, because the system is linear only for a frequency closed to the resonance frequency.

2-2-2. Electromechanical coupling coefficient

The electromechanical coupling coefficient k determines the conversion efficiency between electrical and mechanical energy. It can be determined as:

$$k^2 = \frac{\tilde{\alpha}^2}{(\tilde{K}_{pze} + K_s) C_{pz} + \tilde{\alpha}^2} \quad (9)$$

Previous study [6] shows that, in the case of a resistive load, the power output will increase when *k* increases until a critical value of *k*. After this critical value, $k_{critical}$, the output power power does not increase while *k* increasing. Nevertheless, it is a waste of material to work with *k* too high. It is even worst with a capacitive load as the output power is decreasing when *k* is increasing.

In the case $k < k_{critical}$, we can assume a low coupling for which the vibration force and the beam velocity are in-phase.

2-2-3. Load

The output power is also varying with the load. The output power reaches a maximum for the adaptation load R_{opt}: [6]

$$R_{opt} = \frac{1}{2\pi f C_{pz}} \quad (10)$$

2-3. Simulation Results

m	tip mass	50 g
d	damping	0.1 N.s/m
K_s	beam stiffness	50 N/m
K_{pze}	piezoelectric stiffness (when it is short-circuited)	10000 N/m
α	force factor	0.001 N/V
C_{pz}	clamped capacity	40 nF
r	ratio depending ...	0.2

Table 1. Parameters for numerical simulation on piezoelectric energy harvester

Using these values, figure 2 shows the output power as a function of the coupling coefficient *k* and the load R_{pz}. To get a varying *k*, we have to change the parameter values of the piezoelement in simulation. In this case, we can write the equations 11, where $x \leq 1$. All the simulations are done at the resonance frequency; but it depends on the value of x, as written in the equation 12.

$$\tilde{K}_{pze} = x \tilde{K}_{pze0} \qquad \tilde{\alpha} = x \tilde{\alpha}_0 \qquad C_{pz} = x C_{pz0} \quad (11)$$

$$f_{respz} = \frac{1}{2\pi} \sqrt{\frac{\tilde{K}_{pze} + K_s}{m}} = \frac{1}{2\pi} \sqrt{\frac{x \tilde{K}_{pze0} + K_s}{m}} \quad (12)$$

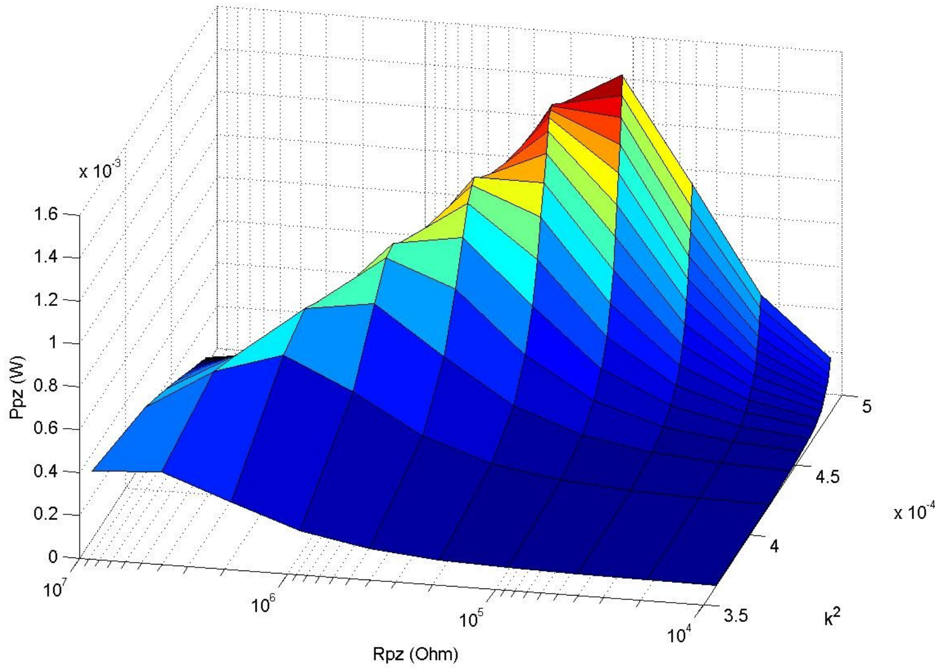


Figure 2. The simulation results of Piezoelectric power output versus varying k and R_{pz}

In figure 2, we can notice that the coupling coefficient k is smaller than its critical value $k_{critical}$, because the power output is always increasing while k increasing. Actually, in this case, $k \ll 1$, which implies a weakly coupling system, and the mechanical vibration will not effected by the energy extracted from the electromechannical interface. The maximal power output is obtained for the maximal value of k, it means for $x = 1$. The maximal power output is 1.5 mW, obtained for a resistive load of 10^5 Ω.

3. ELECTROMAGNETIC POWER HARVESTING DEVICE

The electromagnetic device consists of a cantilever beam, with a magnet fixed at its free end. With the movement of the beam, the magnet is moving in a coil, inducing current flow in the coil loop.

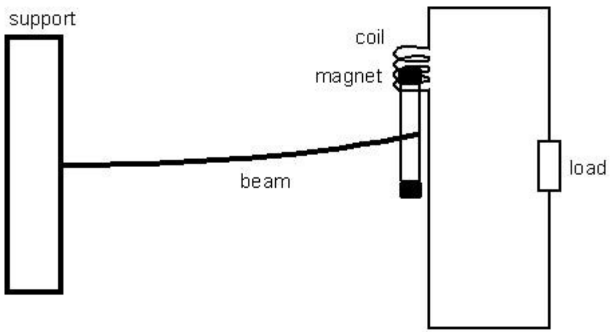


Figure 3. Schematic of electromagnetic power harvester setup

3-1. Modeling

Near the resonance frequency, if the displacement remains small enough to keep a linear movement, the electromagnetic structure can be modeled as a simple uniaxial system {mass+magnetic+stiffness+damping}. This model is analog to the previous one for the piezoelectric structure.

The equations of this model are the following:

$$F_{mg} = B l_{coil} I_{mg} \tag{13}$$
$$V_{mg} = B l_{coil} \dot{u} - L_{mg} \dot{V}_{mg} / R_{mg} \tag{14}$$
$$m \ddot{u} = F - B l_{coil} I_{mg} - K_s u - d \dot{u} \tag{15}$$
$$V_{mg} = R_{mg} I_{mg} \tag{16}$$

It conducts to the following system:

$$\begin{pmatrix} \dot{V}_{mg} \\ \dot{u} \\ \ddot{u} \end{pmatrix} = \begin{pmatrix} \frac{-R_{mg}}{L_{mg}} & 0 & \frac{R_{mg} B l_{coil}}{L_{mg}} \\ 0 & 0 & 1 \\ \frac{-B l_{coil}}{R_{mg} m} & \frac{-K_s}{m} & \frac{-d}{m} \end{pmatrix} \begin{pmatrix} V_{mg} \\ u \\ \dot{u} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \hat{F} \sin(2\pi t/T) \end{pmatrix} \tag{17}$$

3-2. Optimization of the harvested power

As for the piezoelectric case, we can write the expression of the parameters on which we are focusing to determine the optimal parameters of the device and get the maximum power output. Here are the expressions of the resonance frequency, f_{resmg} the electromagnetic coupling factor, k, and the optimal load, R_{opt}:

$$f_{resmg} = \frac{1}{2\pi} \sqrt{\frac{K_s}{m}} \tag{18}$$
$$k^2 = \frac{(B l_{coil})^2}{K_s L_{mg} + (B l_{coil})^2} \tag{19}$$
$$R_{opt} = 2\pi f L_{mg} \tag{20}$$

3-3. Simulation Results

m	mass of the magnet	50 g
d	damping	0.1 N.s/m
Ks	beam stiffness	50 N/m
B	magnetic field of the magnet	0.5 T
L_{mg}	inductance of the coil	1 mH
l	length of the conductor of the coil	5 m

Table 2. Parameters used for electromagnetic energy harvesting simulation

We use the values of the table 2 in the model. As for the piezoelectric simulation, k varies depending on the size of the coil:

$$L_{mg} = x\, L_{mg0};\, l = x\, l \tag{21}$$

In this case, the resonance frequency is not changing with x and all the study is with the same frequency which is resonant frequency of the cantilever beam. We obtained the following power output for the different values of coupling coefficient k and the resistive load. Whereas we assumed a low coupling in the piezoelectric model, we can not assume the same in this electromagnetic model: the coupling coefficient is closed to 1, and the maximal power output remains the same (18 mW) for the different values of x, with vibration amplitude of 20m. As explained before, it is more interesting to work in the low coupling. But, as we can see on the curve, the optimal load to get the maximum power output of 18 mW depends on the value of k. In the real case, it is not interesting to work with a "small" load (as a short-circuit). It means that we have to find a compromise between the value of the load, the waste of material, and the power output we would like to get.

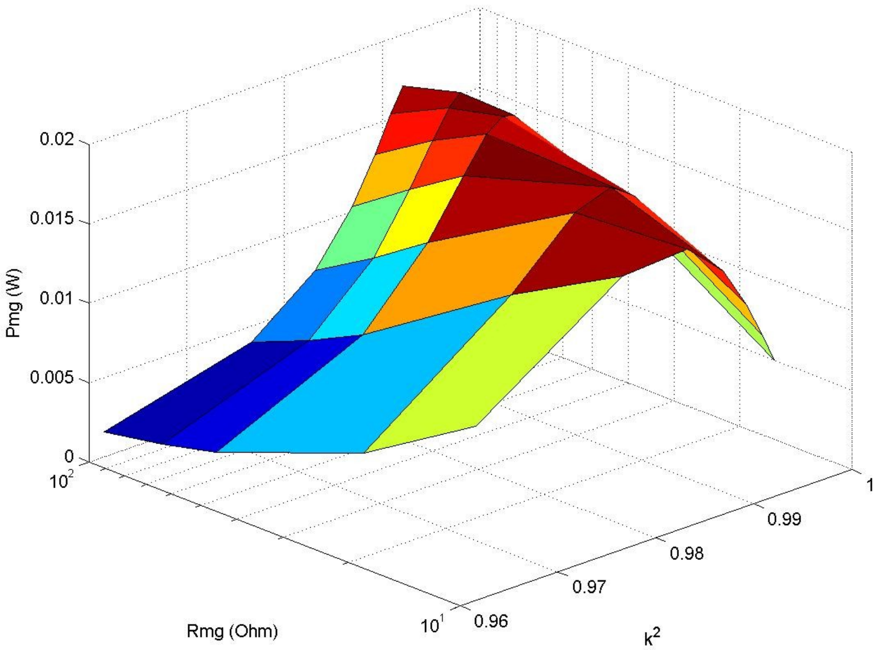


Figure 4. Power output from electromagnetic power output with varying *k* and R_{mg}

4. HYBRID POWER HARVESTING DEVICE

For the hybrid power harvesting device shown in figure 5. The idea is to reusing coil inductance when the beam tip is moving to the opposite side. When the beam tip vibrates to the upper maximum point, the magnet attached on the beam tip will go through the upper coil, and generate inductive current which is feeding into the load with K_1 switch closed while the lower coil is free at this time and can be used as an inductor in the piezoelectric energy harvester switching interfacing circuit. And vice versa, when the beam tip is vibrating to the lowest minimum point, K_2 is closing to deliver inductive current into load while the upper coil is free and can be used as an inductor in switching circuit.

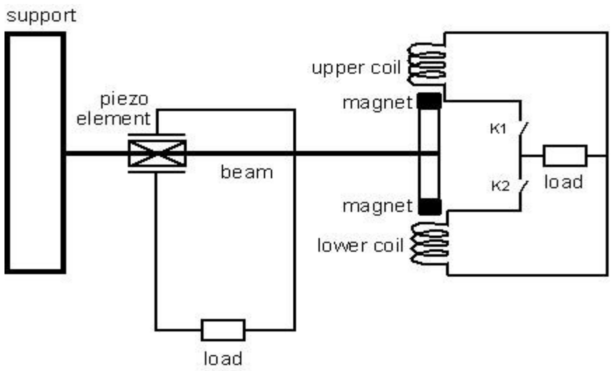


Figure 5. Reusing of coil inductance mecanism on the electromagnetic side

4-1. Modeling

The model is analog to the two previous ones. A coupling between the two harvesting systems appears since the displacement is the same for both systems. The equations for the hybrid device are the following:

$$m\ddot{u}=\hat{F}\sin(2\pi t/T)-\tilde{K}_{pze}u-\tilde{\alpha}V_{pz}-Bl_{coil}I_{mg}-K_s u-d\dot{u} \quad (22)$$

$$I_{pz}=\tilde{\alpha}\dot{u}-C_{pz}\dot{V}_{pz} \qquad V_{pz}=R_{pz}I_{pz} \quad (23)$$

$$V_{mg}=Bl_{coil}\dot{u}-L_{mg}\dot{I}_{mg} \qquad V_{mg}=R_{mg}I_{mg} \quad (24)$$

With these equations, we can hybrid device equations as,

$$\begin{pmatrix}\dot{V}_{pz}\\ \dot{V}_{mg}\\ \dot{u}\\ \ddot{u}\end{pmatrix}=\begin{pmatrix}\frac{-1}{C_{pz}R_{pz}} & 0 & 0 & \frac{\tilde{\alpha}}{C_{pz}}\\ 0 & \frac{-R_{mg}}{L_{mg}} & 0 & \frac{R_{mg}Bl_{coil}}{L_{mg}}\\ 0 & 0 & 0 & 1\\ \frac{-\tilde{\alpha}}{m} & \frac{-Bl_{coil}}{R_{mg}m} & \frac{-(\tilde{K}_{pze}+K_s)}{m} & \frac{-d}{m}\end{pmatrix}\begin{pmatrix}V_{pz}\\ V_{mg}\\ u\\ \dot{u}\end{pmatrix}+\begin{pmatrix}0\\ 0\\ 0\\ \hat{F}\sin(2\pi t/T)\end{pmatrix} \quad (25)$$

4-2. Optimization of the harvested power

As this new system is more complicated than the two working alone, it is now difficult to predict the optimal parameters. The resonance frequency is defined by the equation 26, but there is not simple expressions for the optimal coupling factors and for the optimal loads because of the coupling between both piezoelectric and electromagnetic parts.

$$f_{respz}=\frac{1}{2\pi}\sqrt{\frac{\tilde{K}_{pze}+K_s}{m}} \quad (26)$$

We only study the variation of power output depending on the resistive loads, for a fixed electromechanical coupling factors.

4-3. Simulation Results

For the situation, both piezoelectric and electromagnetic system working simultaneous and connected to a restive load respectively. The power output versus the piezoelectric load resistance R_{pz} and the electromagnetic load resistance R_{pz} are plotted in figure 6.

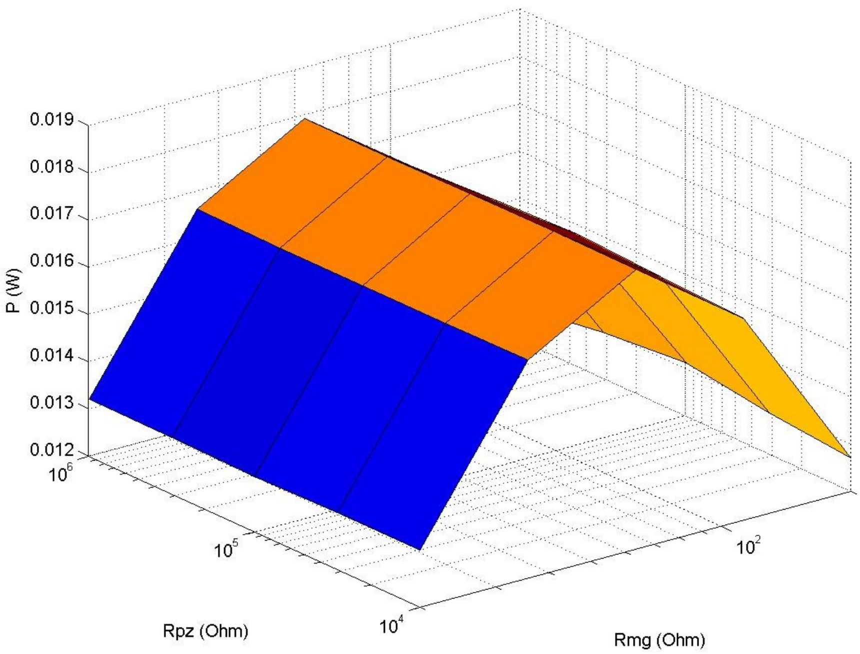


Figure 6. Power output from the hybrid energy harvesting device.

The global output power from the hybrid device depends on the value of R_{mg} and is independent on the value of R_{pz}. There is two reasons to explain it. First, the output power of the piezoelectric part is very small in comparison with the output power of the electromagnetic part. Indeed, the maximum output power of the piezoelectric part is around 1 mW versus 18 mW for the electromagnetic part in this simulation. Second, the electromechanical coupling coefficient is much higher for the electromagnetic part than for the piezoelectric part, so the displacement will be strongly determinate by the electromagnetic part. Moreover, due to the difference of coupling factor, for the same displacement (as it is the case here), the output power will be higher for the electromagnetic par, as we already noticed. Figure 7(a) and 7(b) shows the respectively power output from the piezoelectric and electromagnetic parts for the hybrid case here.

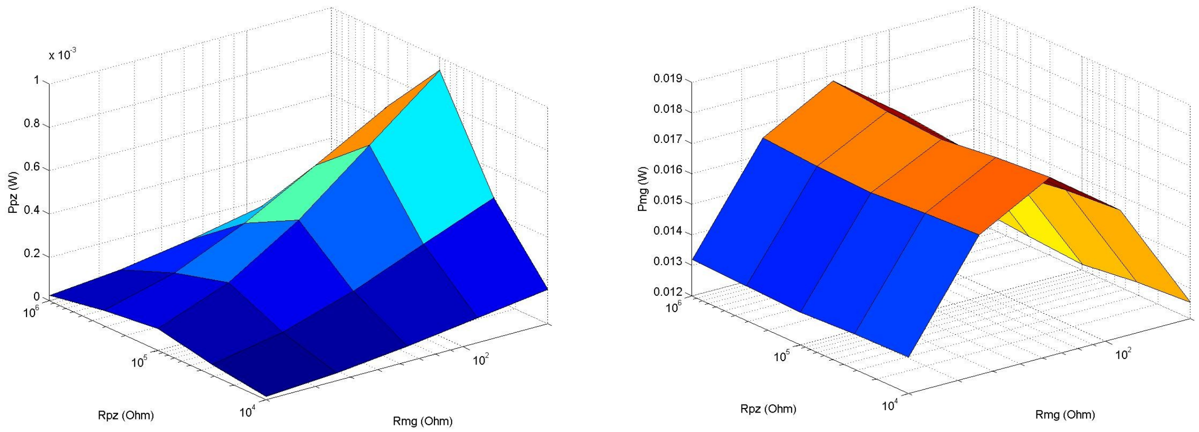


Figure 7 (a)Power output from piezoelectric part for the hybrid case (b) Power output from the electromagnetic part for the hybrid case.

4-4. Switching Mechanism for Reusing Coils as Inductors

In the ideal case, we would like to combine the two parts of the device using one common load. As most of the loads need DC current, we also need two rectifiers. With a single common load for both the piezoelectric and electromagnetic output, and improve the piezoelectric part reusing the coil in a switching circuit which can boost performance of the piezoelectric part. The schematic of switching mechanism is shown in figure 8. Indeed, when the beam tip vibrates to the upper maximum point, the magnet will go through the upper coil, and generate inductive current which is feeding into the storage capacitor with K_{a1} and K_{b1} switches closed. At this time, the lower coil is free, the K_{c1} switch remains closed during this period and the K_{d1} switch is closed to discharge the charge stored in piezoelectric internal static capacitor into the common load through the lower coil. And vice versa, when the beam tip is vibrating to the lowest minimum point. The two states are shown in the Figure 9.

Obviously, it will be difficult to realize this ideal case since the values of optimal loads are not the same for both parts, and there must be another interfacing circuit to force extracting energy from the piezoelectric and electromagnetic parts which will be studied in the future.

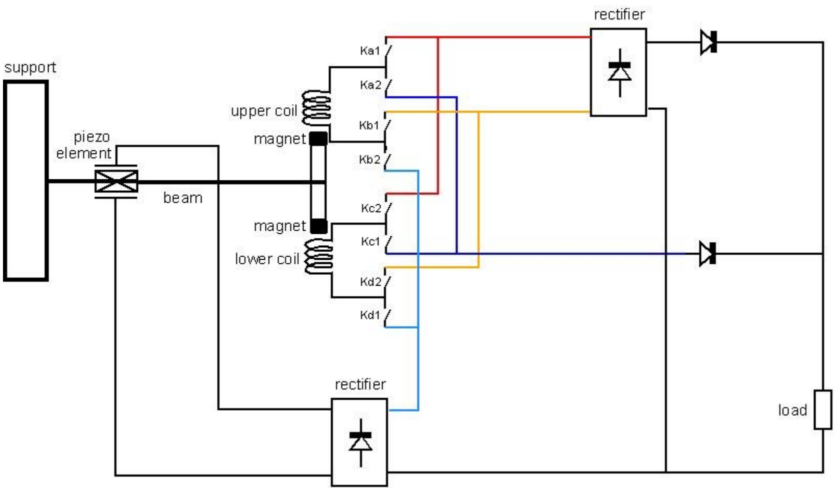


Figure 8. Switching mechanism of reusing coils as inductors and charing a common load

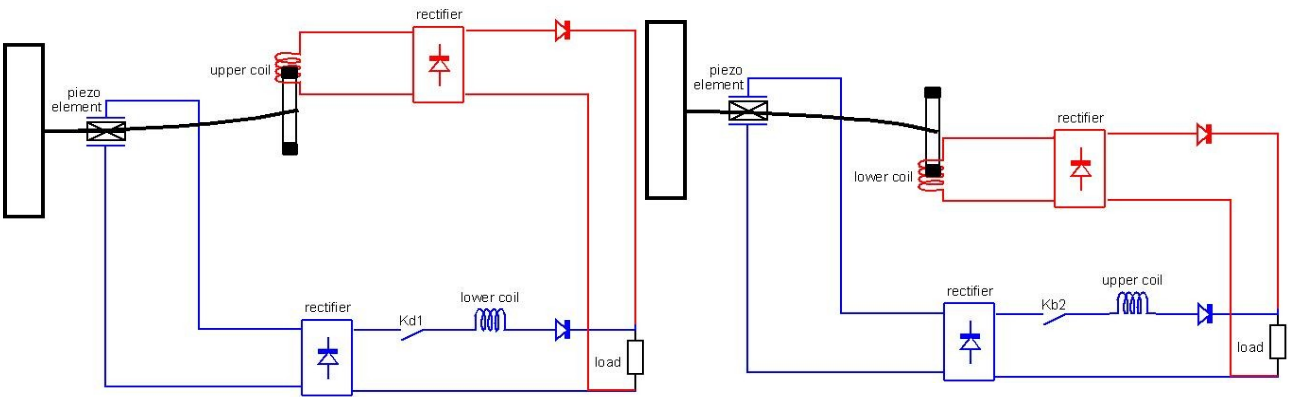


Figure 9. Equivalent circuit for alternating coils as a power generator and an inductor in switching circuit.

5. Experiment Validation

The photo of first prove of concept experimental setup is shown in figure 10. There are two magnets as proof mass attached on the top and bottom at the tip of the cantilever beam .

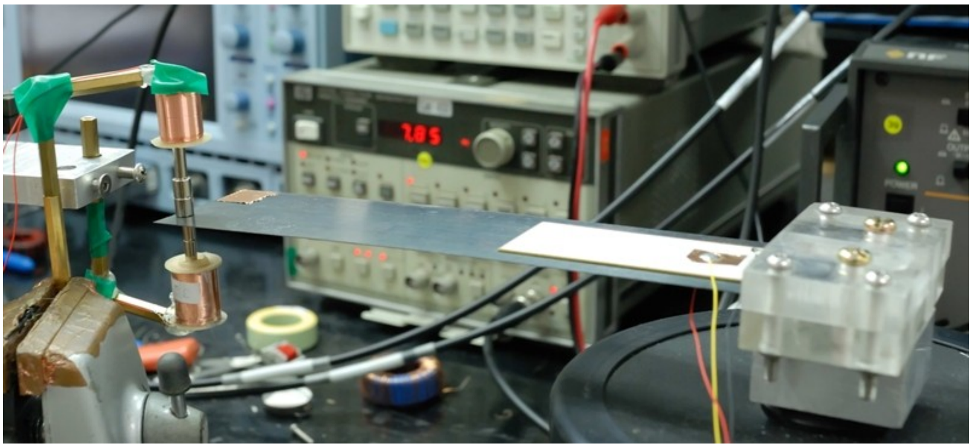
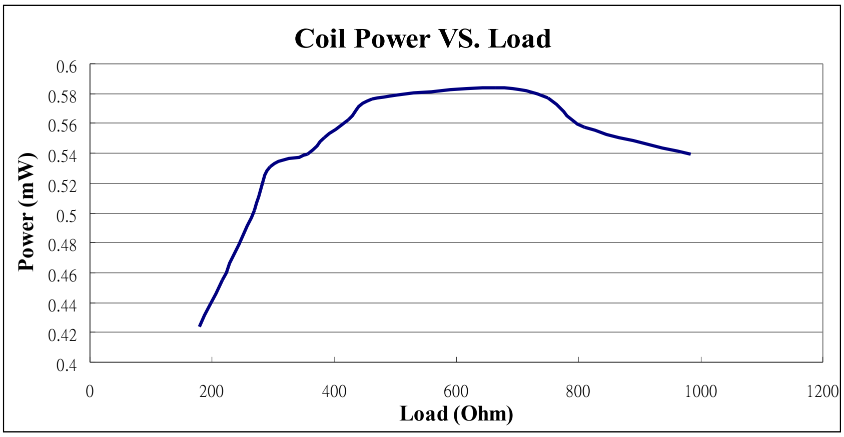
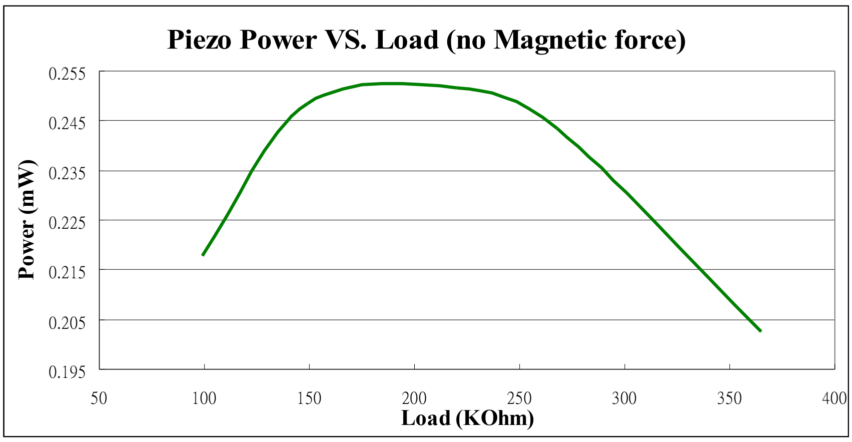


Figure 10. The photo of the experiment setup

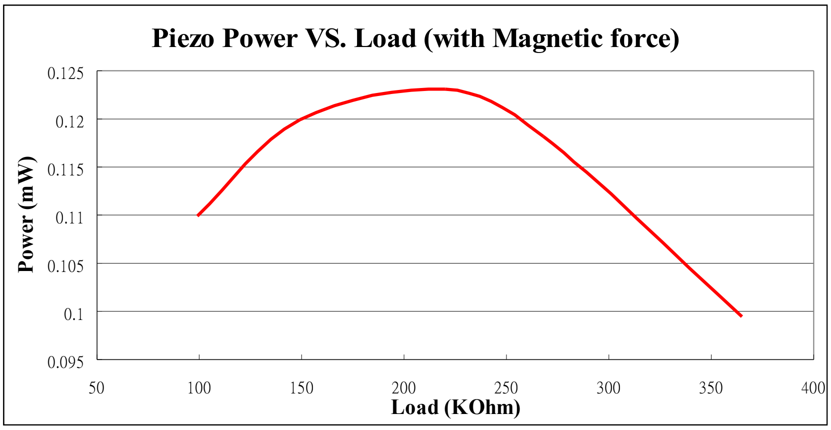
The power output from the coil under different loading resistance is plotted in figure 11(a). The piezoelectric part power output under different loading condition without and with coils closed to the magnets are plotted in figure 11(b) and figure 11(c) receptively. From the plots we can see there are a matching resistance value as predicted in the model which will have peak power output for both the piezoelectric and electromagnetic only case.



(a)



(b)



(c)

Fig. 11 (a) Power output of electromagnetic energy harvesting under different load resistance (b) Power output of piezoelectric energy harvesting under different loading resistance with magnet proof masses and no coils closed to the magnets (c) Power output of piezoelectric energy harvesting under different loading resistance with magnet proof masses and coils closed to the magnets

According to the above experiments, the power output from piezoelectric only system and the hybrid power harvesting device could be compared and summarized in Table 3 with separately matching loads for piezoelectric and electromagnetic parts. If the load was well designed to be matched the impedance of the coil and piezoelectric, the power output from the piezoelectric only case is 0.25mW and the hybrid power harvesting device could generate 0.703mW in total. For the piezoelectric part, the output is drop to around zero for the hybrid case compared to the piezoelectric only case because of the reduced vibration level under high electromagnetic coupling. However, the total power output is still around 3 times for the hybrid device compared with the piezoelectric only case. The output power from piezoelectric part can be further boosted for 3 to 4 times with the switching techniques , like SSHI interface. However, the interfacing circuit should be further designed to deliver the power output into a common load or a common storage buffer which will be further studied in the future.

	Piezoelectric Only	Hybrid Power harvesting Device
Electromagnetic (mW)	0	0.58
Piezoelectric (mW)	0.25	0.123
Total Power (mW)	0.25	0.703

Table 3. Comparison chart of power output from piezoelectric only and hybrid energy harvesting devices.

6. CONCLUSION

In this paper, the piezoelectric and electromagnetic output from hybrid vibration energy harvesting system are modeled and studied. A mechanism of reusing the coils in generating power and also acted as inductors in the switching circuit which can boost power from the piezoelectric part is also proposed. A first prove of concept experiment also verified that the hybrid system will generate around 3 times power compared to the piezoelectric only case. The output power from piezoelectric part can be further boosted for 3 to 4 times with the switching techniques , like SSHI interface. However, the interfacing circuit should be further designed to deliver the power output into a common load or a common storage buffer which will be further studied in the future.

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