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# MEMS 复合式振动能量采集器

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**摘要**:介绍了一种结合了压电式能量采集与静电式能量采集原理的复合式振动能量采集器。其结构通过有限元分析软件的优化设计,得到了期望的低频共振频率。为了预测这个复合式振动能量采集器的性能,建立了解析模型,在此基础上使用 MATLAB/SIMULINK 进行了数值模拟。模拟结果显示,在某些特定的频率范围内,这种复合式振动能量采集器能够提供比其他两种能量采集器更高的输出功率。对于固有频率为 282 Hz 的器件结构,仿真发现复合式设计的输出功率可达 4.85 μW,两倍于电容式设计的输出功率 2.11 μW。

**关 键 词**:压电能量采集器;静电能量采集器;复合式能量采集器;微机电系统
**中图分类号**:TN384;TN712 **文献标识码**:A

# MEMS hybrid power-generator from vibration energy

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**Abstract:** A hybrid vibration-powered microgenerator has been presented by combining the structures of piezoelectric generator and electrostatic generator, and the structure of the microgenerator is optimized by a Finite Element Method (FEM) to obtain the desired low resonant frequency. Then, an analytic model is established to predict the behavior of the hybrid power-generator and a MATLAB/SIMULINK is utilized for the numerical simulation. The simulated results reveal that the hybrid power-generator has a higher output power than those of two energy harvesting mechanisms at a special resonant frequency. For a resonant frequency of 282 Hz, the simulation result shows the output power from the hybrid mechanism is 4.85 μm, which doubles 2.11 μW from the original capacitive mechanism.

**Key words:** piezoelectric power generator; capacitive power generator; hybrid micro power generator; MEMS

## 1 Introduction

Much work has been done on the development of the different energy harvesters which can convert the vibration energy into the electrical power to drive wireless systems[1]. The main converting mechanisms are piezoelectric mechanisms, capacitive mechanisms and electromagnetic mechanisms[2]. In this paper, we present a

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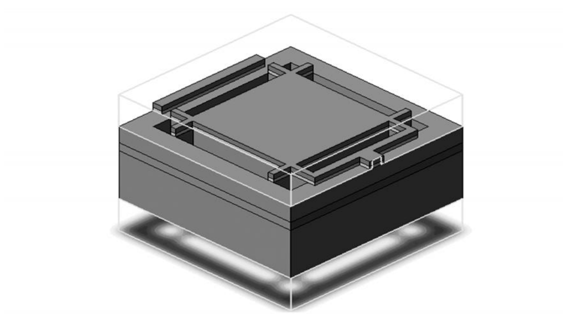
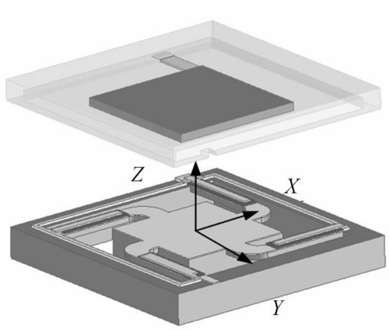
design combining the capacitive and piezoelectric energy harvesting mechanisms. The design can be fabricated by MEMS technology in a compact structure to form a MEMS hybrid energy harvester.

## 2 Design principle

The design is based on a capacitive energy harvester structure which is known as Out-of-plane gap closing type[3], as shown in Fig. 1(a). The mass and cantilevers are fabricated by deep reactive ion etching process (DRIE) on a silicon wafer. The two glass wafers with the cave are bonded onto the silicon wafer to define the vibration space for the mass. Two different metals (Pt and Al) are deposited on the mass and glass respectively to form two electrodes of the capacitor. The work function difference of the two metal electrodes can offer the initial bias voltage for the energy harvester so that the external bias voltage can be avoided.



(a) Typical capacitive energy harvester




(b) Hybrid design

Fig. 1 Principle structure of energy harvester

In our design, when the mass is vibrated, the distance between the two electrodes changes, and then a variable capacitor is formed. The vibration of the mass will lead to the variation of charges stored in the capacitor, thus provides current for the load. To improve the efficiency of the energy converting, the piezoelectric film can be deposited on cantilever beams by using the sol-gel process. Under the driving of a vibration source, the cantilever beams bend, and the surface stress of the piezoelectric film in $X$ or $Y$ direction will cause the voltage on $Z$ direction. This design can fully make use of the vibration energy, and will certainly improve the performance of the energy harvester.

The cantilever beams were designed with the L shape to prolong the length of the piezoelectric film and reduce the natural frequency of the structure. The Fig. 1(b) depicts the schematic design of this hybrid energy harvester.

## 3 Analytic modeling

Most analytic models for vibration energy harvester are based on the linear theory proposed by Williams and Yates[4]. According to this theory, the conversion of the vibration energy into the electrical power can be considered as an extra damping, e. g., electrical damping. The dynamics of the energy harvester can be expressed by

$$m\frac{\partial^2 z}{\partial t^2} + (b_e + b_m)\frac{\partial z}{\partial t} + k\cdot z = ma, \qquad (1)$$

where $m$, $k$, $z$, $b_m$, $b_e$, $a$ are the mass, spring constant, mass displacement in $Z$ direction, the mechanical damping coefficient, the electrical damping coefficient, and the external acceleration.

### 3.1 Capacitive harvester modeling

The current generated by the capacitive harvester can be expressed by

$$i = \frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(V\cdot C) = V\cdot\frac{\mathrm{d}C}{\mathrm{d}t} =$$

$$\varepsilon\cdot A\cdot V\cdot\frac{\mathrm{d}\frac{1}{g_0 - z}}{\mathrm{d}t} = \frac{\varepsilon\cdot A\cdot V}{(g_0 - z)^2}\cdot\frac{\mathrm{d}z}{\mathrm{d}t}, \qquad (2)$$

where $V$, $A$, $g_0$, $\varepsilon$ stand for the voltage across the capacitor, the overlap area of the two electrodes, the original distance between two electrodes, and the dielectric constant for the free space, respectively. For a load resistance $R$, the power output of the harvester can be expressed as:

$$P = i_R^2 \cdot R = \frac{i^2 \cdot R}{(\omega R C_{cap} + 1)^2} = \left(\frac{\varepsilon \cdot A \cdot V}{(g_0 - z)^2}\right)^2 \cdot \frac{R}{(\omega R C_{cap} + 1)^2} \cdot \left(\frac{dz}{dt}\right)^2, \quad (3)$$

where the $C_{cap}$ is the initial capacitance at no vibration. The electrical damping is given as:

$$b_e = \left(\frac{\varepsilon \cdot A \cdot V}{(g_0 - z)^2}\right)^2 \cdot \frac{R}{\omega R C_{cap} + 1}, \quad (4)$$

The electrostatic force between the electrodes is given as:

$$F_{ele} = \frac{Q^2}{2 \cdot \varepsilon \cdot A} = \frac{\varepsilon \cdot A \cdot V^2}{2 \cdot (g_0 - z)^2}, \quad (5)$$

Using Eq. (2) to Eq. (5), the dynamics of the capacitive harvester can be expressed as

$$m \cdot a = m \cdot \frac{d^2 z}{dt^2} + \left(b_m + \left(\frac{\varepsilon \cdot A \cdot V}{(g_0 - z)^2}\right)^2 \cdot \frac{R}{\omega R C_{cap} + 1}\right) \cdot \frac{dz}{dt} + k \cdot z + F_{ele}, \quad (6)$$

### 3.2 Hybrid harvester modeling

The electrical damping of the hybrid harvester is composed of two parts, the piezoelectric part and capacitive part. For piezoelectric part, the current created by the stress of the piezoelectric film can be expressed by[5]

$$i_{pzt} = \frac{4 \cdot d_{31} \cdot Y_{PZT} \cdot w_{PZT}}{\sqrt{1 + \left(\frac{L}{Z}\right)^2}} \cdot \frac{L_{PZT}}{L} \cdot \frac{dZ}{dt}, \quad (7)$$

where $d_{31}$ is the piezoelectric constant in the 31 coupling direction, $Y_{pzt}$ is the Young's modulus of the piezoelectric film in 1 direction, $w_{pzt}$ is the width of the piezoelectric film, $L$ is the length of the cantilever, and $L_{pzt}$ is the length of the piezoelectric film.

As summary, the analytic model for the hybrid harvester can be presented as following:

$$\begin{cases} m \cdot a = m \cdot \frac{d^2 z}{dt^2} + (b_m + b_e) \cdot \frac{dz}{dt} + k \cdot z + F_{ele} \quad (z \leq g_0) \\ F_{ele} = \frac{\varepsilon \cdot A \cdot V^2}{2 \cdot (g_0 - z)^2} \\ b_e = \left(\frac{\varepsilon \cdot A \cdot V}{(g_0 - z)^2} + \frac{4 \cdot d_{31} \cdot Y_{PZT} \cdot w_{PZT}}{\sqrt{1 + \left(\frac{L}{Z}\right)^2}} \cdot \frac{L_{PZT}}{L}\right)^2 \cdot \frac{R}{\omega R C + 1} \\ P = \frac{R}{(\omega R C + 1)^2} \cdot \left(\frac{\varepsilon \cdot A \cdot V}{(g_0 - z)^2} + \frac{4 \cdot d_{31} \cdot Y_{PZT} \cdot w_{PZT}}{\sqrt{1 + \left(\frac{L}{Z}\right)^2}} \cdot \frac{L_{PZT}}{L}\right)^2 \cdot \left(\frac{dZ}{dt}\right)^2 \\ C = C_{cap} + C_{pzt} \end{cases}, \quad (8)$$

where $C_{pzt}$ is the capacitance of the piezoelectric film in $Z$ direction. $P$ is the harvested power for the hybrid energy harvesting mechanism.

## 4 Simulation results

Generally, vibration-powered harvesters are working under the resonant state, so the natural frequency is critical in the design for the optimized performance. The natural frequency of structure can be investigated by ANSYS simulation[6]. The relationship between the natural frequency in $Z$-axis and the dimension of structure is shown in Fig. 2, where $T_{si}$ is the thickness of the cantilever, $L_m$ is the length of mass. The external acceleration is defined as $0.2g$ ($g$ is the acceleration of gravity). Then MATLAB/SIMULINK is utilized for the analytic modelling. Fig. 3 (a) and Fig. 3 (b) show the harvesting power distribution for two different energy harvesting mechanisms.

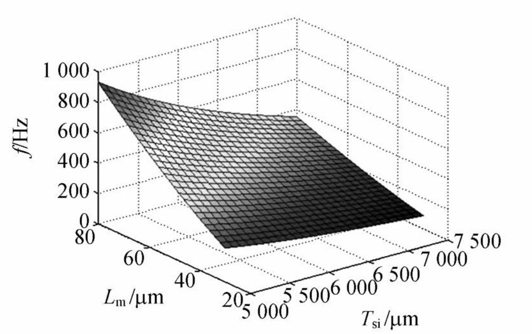
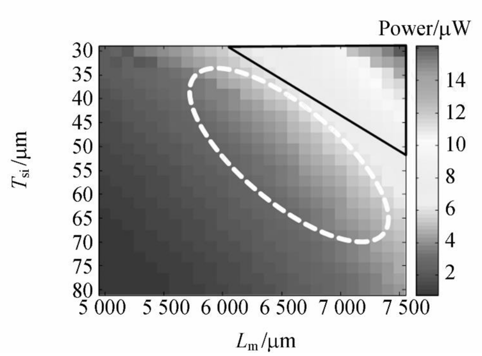
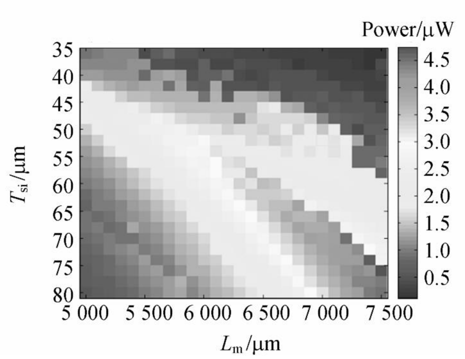



Fig. 2 Natural frequency of structure versus the thickness of cantilever and the length of mass




(a) Hybrid energy harvesting mechanism




(b) Capacitive energy harvesting mechanism

Fig. 3 Harvested power versus the thickness of cantilever beam and the length of mass

The output power is very high in the top right corner of Fig. 3 (a) which has been indicated by the black triangle. But the harmonic analysis of ANSYS shows that the stresses of piezoelectric film in the structures indicted by the black triangle range exceed the maximum allowed tensile strength of 34.5 MPa[7], which will cause the degeneration of the piezoelectric film.

By comparison of two images of Fig. 3, the hybrid mechanism can highly improve the output power of the structures with the natural frequencies within the range of 200 - 400 Hz (as enclosed by white dash ellipse in Fig. 3 (a). e. g., for the structure with the thickness of the cantilever beams of 62 μm, the length of mass of 7 100 μm, the natural frequency is 282 Hz. The simulation result shows the output power can be doubled from 2.11 μW with the capacitive mechanism to 4.85 μW with the hybrid mechanism.

## 5 Conclusions

In this research, a hybrid vibration-powered generator combining the merits of capacitive mechanism and piezoelectric mechanism is designed to improve the performance of the capacitive energy harvesting mechanism. Based on the analytic model and the result of the model structure analysis from ANSYS, the dynamic behaviour of the device is simulated by MATLAB/SIMULINK. Simulation results show that the maximum output power of the hybrid mechanism has increased by 26 % - 200 % as compared with that of capacitive mechanism for the structures with the natural frequencies in the range of 200 - 400 Hz.

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**●下期预告**

# 机械感生长周期光纤光栅实验研究


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为了研究机械感生长周期光纤光栅(MLPFGs)的特性,利用机械微弯法写制了长周期光纤光栅。首先,采用机械先加工技术制作了周期性压力槽。然后,通过设计机械写制结构,制作了MLPFGs,并实验验证了该光栅与周期性压力槽的周期、周期数以及外加应力等参数与MLPFGs透射谱的关系。最后,研究了温度对带有涂敷层和无涂敷层单模光纤写制的MLPFGs的影响。实验表明:MLPFGs的最大谐振峰值可达16 dB,插入损耗 $< 0.5$ dB;通过改变压力槽的周期,实现了谐振波长 $> 14$ nm的调谐范围;带有涂敷层和无涂敷层单模光纤写制的MLPFGs谐振波长的温度灵敏度分别为0.057 nm/℃和0.086 nm/℃,谐振峰值的温度灵敏度分别为0.230 dB/℃和0.312 dB/℃。该写制结构能较好地控制MLPFGs的透射谱,同时结构简单、易擦除、成本低。在光纤传感领域具有一定的应用价值。