Chapter 2

Integrated Power Supply for MEMS Sensor

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Additional information is available at the end of the chapter

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Abstract

The recent expansion of wireless sensor networks and the rapid development of low-power consumption devices and MEMS devices have been driving research on harvester converting ambient energy into electricity to replace batteries that require costly maintenance. Harvesting energy from ambient environment vibration becomes an ideal power supply mode. The power supply module can be integrated with the MEMS sensor. There are many ways to convert ambient energy into electrical energy, such as photocells, thermocouples, vibration, and wind and so on. Among these energy-converting ways, the ambient vibration energy harvesting is more attractive because the vibration is everywhere in our daily environment. Based on the analysis of the basic theory of the electret electrostatic harvester, the basic equations and equivalent analysis model of electret electrostatic harvester are established. The experimental tests for the output performance of electret electrostatic harvester are completed. For the electret material, the material itself can also provide a constant voltage to avoid the use of additional power, which provides an effective way for electrostatic harvesting. Therefore, the electret electrostatic harvesting structure is a kind of ideal energy harvesting method using ambient vibration and can be easily integrated with the MEMS system.

Keywords: integrated, MEMS, vibration, energy harvesting, electromagnetic harvester

1. Introduction

With the development and progress of science and technology, information technology has already entered the era of micro-nano, and the emergence and development of large-scale integrated circuits have made great and rapid progress in computer technology, information technology, and control technology [1–4]. With the development of micro-nano-technology, the volume of the sensor becomes smaller and smaller, and the signal processing circuit becomes smaller and smaller. The overall system has become smaller, but the power supply has not become smaller [5, 6].

With the system becoming smaller, the energy power required is also getting smaller, but the power supply must be wired. Independent battery energy has limited energy, and its own energy is decaying, requiring periodic replacement or periodic charging, which is an extremely difficult or almost impossible task for an information system that requires long-term work or working in a confined space things. Therefore, an energy harvesting system that takes advantage of ubiquitous energy in the environment is imperative [4–6].

According to the application characteristics of MEMS wireless sensors, harvesting energy from ambient environment vibration becomes an ideal power supply mode. The power supply module can be integrated with the MEMS sensor. There are many ways to convert ambient energy into electrical energy, such as photocells, thermocouples, vibration, and wind and so on [7, 8]. Among these energy converting ways, the ambient vibration energy harvesting is more attractive because the vibration is everywhere in our daily environment [9, 10]. So it has broad application to convert energy directly from the ambient vibration.

Compared with the traditional chemical batteries, micro-vibration energy harvester has the following advantages:

1. Long-term storage. Micro-energy harvester can directly convert the mechanical energy into electrical energy. This will overcome the shortcoming of electrical energy release due to long-term storage of the traditional battery.
2. Small size and high energy density. It is much smaller than the traditional battery size and has higher energy density.
3. Easy to integrate. The manufacturing technology of the micro-harvester structure is compatible with the manufacturing process of MEMS so as to realize the integration of the overall system (including the micro-power supply, the micro-mechanical structure, and the circuit system).
4. Low cost. The harvesting structures are easy to integrate with the MEMS structures for mass production. Therefore, the production and maintenance cost can be greatly reduced.

According to the analysis, the vibration energy harvester possesses many advantages that other micro-energy sources do not have. Therefore, the research on the vibration harvester has become a hotspot in the field of micro-energy [11–13]. Recently, the energy harvesting mechanism of vibration energy harvesting mainly includes four types: piezoelectric, electromagnetic, electrostatic, and magnetostrictive [12, 14]. Among these mechanisms, the electrostatic harvesting is suitable for MEMS device power supply because the electrostatic materials are easy to integrate with the micro-mechanical structures.

2. Electrostatic vibration energy harvesting

Self-powered microsystems are implemented as MEMS technology enables miniaturization of devices and MEMS monoliths can be monolithically integrated with other MEMS devices. For the current MEMS technology, compatible with MEMS technology to achieve self-powered MEMS system service technology is mainly electrostatic harvesting technology.

Electrostatic vibration energy harvesting is a kind of energy harvesting method through variable capacitance to generate electrical energy. When the capacitance of the variable capacitor is changed due to the vibration of the external environment, the amount of charge stored in the capacitor is changed. And a charge flow formed in the circuit due to the change of capacitor will provide electrical power to the load. The electrostatic harvester has high output voltage and is easy to integrate with MEMS structure. The coupling coefficient of electrostatic harvester is easy to adjust, and the capacitance can be adjusted by adjusting the capacitor size [15].

Generally, electrostatic harvesting system consists of two-unit modules, the vibration unit and the electrostatic harvesting unit. The vibration unit can be regarded as a second-order vibration system composed of a mass spring, which can convert the vibration excitation in the external environment into the kinetic energy of the vibration mass. Electrostatic harvesting unit usually consists of a variable capacitor, a load resistor, and an external power source (such as electret, charging capacitor, or other power source) that converts the kinetic energy of the mass into electrical energy. There are two main types of electrostatic harvester: one is electret-free electrostatic harvester, and the other is based on electret-based electrostatic harvester. The operation mode of electret-free electrostatic harvester is generally divided into constant charge and constant voltage [16–18]. Before the vibration energy harvesting structure starts to output electric energy, an initial voltage needs to be applied to the variable capacitor, and the upper and lower electrodes of the variable capacitor are charged and discharged during energy harvesting. The control circuit of electret-free electrostatic harvester is relatively complicated and difficult to achieve. While the electret of electret-based electrostatic harvester can be regarded as one pole of a variable capacitor, and the vibration energy can be directly converted into electric energy without charging or discharging the variable capacitor [19, 20].

2.1. Variable capacitance model

The output characteristics of electrostatic harvesting system depend on the kinetic energy obtained by vibrating unit and on the energy conversion of the harvesting unit, while the power conversion depends on the size of capacitance and the change rate of capacitance. In order to design a relatively large capacitance in a limited space, people take a variety of ways. A variety of structures have been proposed at the micrometer scale, of which the comb structure is relatively common. Most of these variable capacitance structures originated from the structures used in micro-accelerometers and micro-gyroscopes. There are four major capacitive models, which are:

a. The comb capacitor model based on pitch tuning: The comb capacitors overlap each other and spacing is variable.

b. The comb capacitor model based on area tuning: The comb capacitors overlap each other and the overlap area is variable.

c. The plane capacitance model based on pitch tuning: The two-plate electrodes are parallel to each other and spacing is variable.

d. The plane capacitance model based on area tuning: The two-plate electrodes are parallel to each other and the overlap area is variable.

Since the spacing between combs is relatively small and the area of the combs is relatively large, the capacitance can also be approximated calculated by an infinite plate capacitance calculation model. According to the general formula of infinite panel capacitance calculation model, we can give the calculation of above four models. The capacity of the plate capacitor is not only related to the size, shape, and spacing of the two electrodes but also related to the dielectric between the two plates. When the electret is added between the two plates of the plate capacitor, the capacitance calculation formula of the plate capacitor will change. In terms of the electrostatic harvesting structure, since the variable capacitance between the two electrodes is generally attached to electret, the corresponding calculation formula of the plate capacitance needs to be adjusted. Capacitance values calculated below include the electrets.

The structure of the plate capacitor with the electret is shown in **Figure 1**. The plane capacitor consists of the upper and lower electrodes and an electret. The electret has an air gap with the upper electrode, and the electret attaches to the lower electrode surface. C_1 is the capacitance between electret and the upper electrode; C_2 is the capacitance between electret and the lower electrode. The total capacitance C is

$$C = \frac{C_1 C_2}{C_1 + C_2} = \frac{\varepsilon_0 S}{g_0 + d/\varepsilon_r} \tag{1}$$

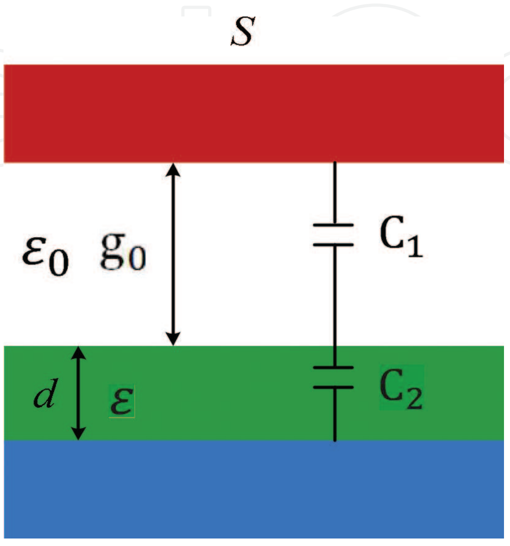

Figure 1. Plate capacitance model.

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where S is the overlap area of the upper electrode and electret, g_0 is the distance between the upper electrode and electret, d is the thickness of electret, and $\varepsilon_r = \varepsilon/\varepsilon_0$ is the relative dielectric constant of the electret.

a. The comb capacitor model based on pitch tuning (**Figure 2**)

The comb capacitor model based on pitch tuning refers to the spacing between the movable comb and the fixed comb that is variable (shown in **Figure 2**), according to the equation $C_{p1}(x) = \frac{\varepsilon_0 S}{g_0 + d/\varepsilon_r - x}$ and $C_{p2}(x) = \frac{\varepsilon_0 S}{g_0 + d/\varepsilon_r + x}$. The total capacitance $C(x)$ is

$$C(x) = N \times \left(C_{p1}(x) + C_{p2}(x)\right) = \frac{2N\varepsilon_0 S\left(g_0 + d/\varepsilon_r\right)}{\left(g_0 + d/\varepsilon_r\right)^2 - x^2} \tag{2}$$

where N is the number of the overlapping comb, S is the overlap area between the movable comb and the fixed comb, g_0 is the initial distance between the movable comb and the fixed comb, d is the thickness of the electret attached to the fixed comb, $\varepsilon_r = \varepsilon/\varepsilon_0$ is the relative dielectric constant of the electrets, and x is the displacement of the movable comb relative to the fixed comb.

b. The comb capacitor model based on area tuning (**Figure 3**)

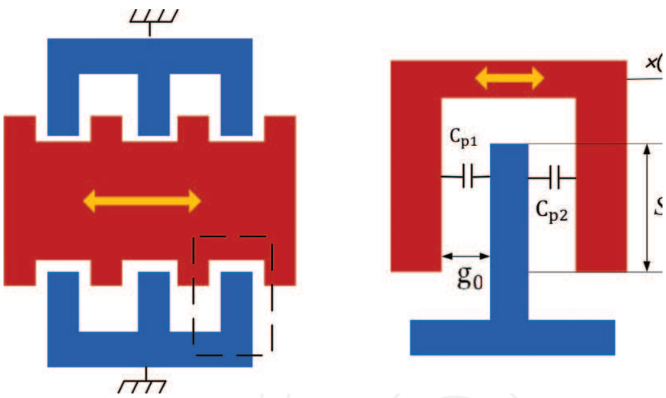

Figure 2. The comb capacitor model based on pitch tuning.

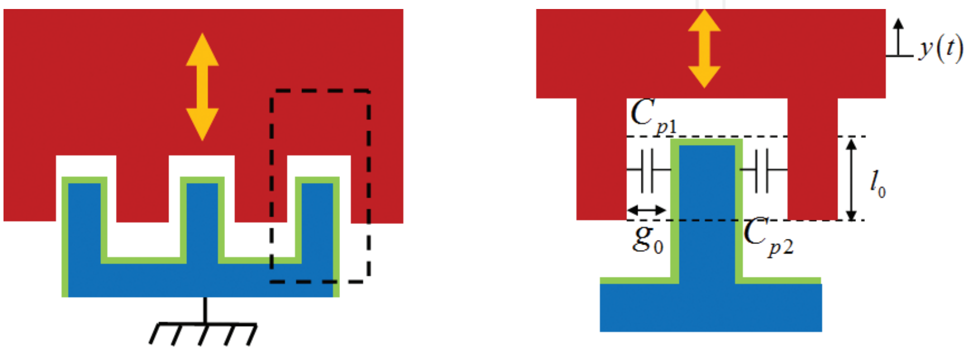

Figure 3. The comb capacitor model based on area tuning.

The comb capacitor model based on area tuning refers to the overlap area between the movable comb and the fixed comb that is variable (shown in **Figure 3**), according to the Eq. (1):

$$C(y) = \frac{2N\varepsilon_0 w}{g_0 + {}^{d}/_{\varepsilon_r}}(l_0 - y) \tag{3}$$

where N is the number of the overlapping comb, l_0 is the overlap length when the movable comb C_{p1} and the fixed comb C_{p2} are in the initial position and $C_{p1} = C_{p2}$, w is the width (depth) of the comb, g_0 is the initial distance between the movable comb and the fixed comb, d is the thickness of the electret attached to the fixed comb, $\varepsilon_r = \varepsilon/\varepsilon_0$ is the relative dielectric constant of the electrets, and y is the displacement of the movable comb relative to the fixed comb.

c. The plane capacitance model based on pitch tuning (**Figure 4**)

The plane capacitance model based on pitch tuning refers to the distance between the two plane electrodes that can be changed (shown in **Figure 4**); according to Eq. (1), the capacitance based on pitch tuning is

$$C(y) = \frac{\varepsilon_0 S}{g_0 + {}^{d}/_{\varepsilon_r} - y} \tag{4}$$

where S is the overlap area between the movable comb and the fixed comb, g_0 is the initial distance between the movable comb and the fixed comb, d is the thickness of the electret attached to the fixed comb, $\varepsilon_r = \varepsilon/\varepsilon_0$ is the relative dielectric constant of the electrets, and y is the displacement of the movable comb relative to the fixed comb.

d. The plane capacitance model based on area tuning (**Figure 5**)

The plane capacitance model based on area tuning refers to the overlap area between the two plane electrodes that is variable (shown in **Figure 5**); according to Eq. (1), the capacitance based on area tuning is

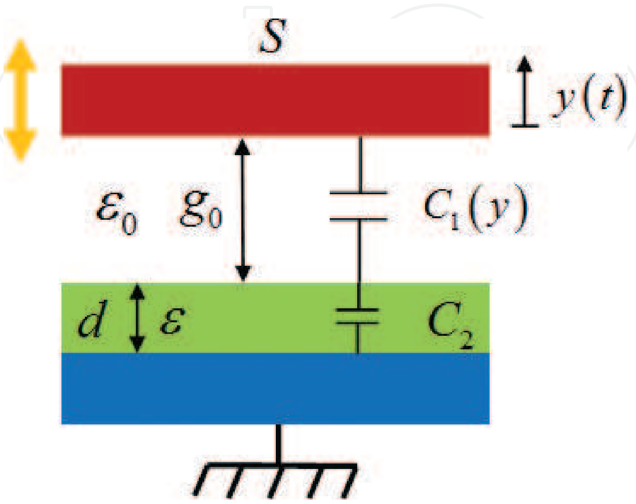

Figure 4. The plane capacitance model based on pitch tuning.

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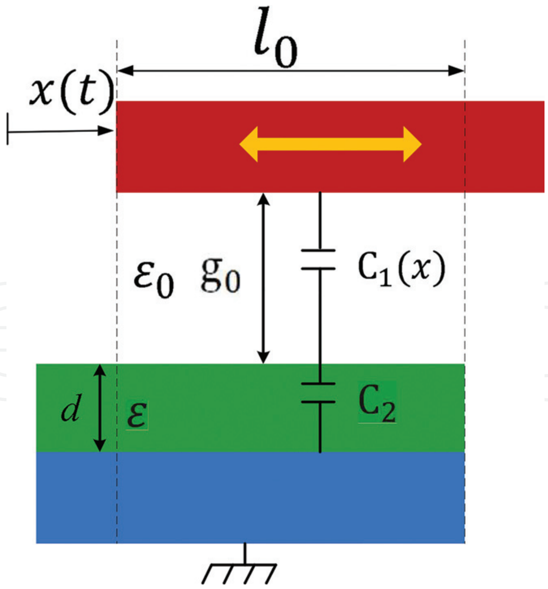

Figure 5. The plane capacitance model based on area tuning.

$$C(x) = \frac{\varepsilon_0 w(l_0 - x)}{g_0 + d/\varepsilon_r} \tag{5}$$

where w is the width (depth) of the comb, l_0 is the overlap length when the movable comb and the fixed comb are at the initial time, g_0 is the initial distance between the movable comb and the fixed comb, d is the thickness of the electret attached to the fixed comb, $\varepsilon_r = \varepsilon/\varepsilon_0$ is the relative dielectric constant of the electrets, and x is the displacement of the movable comb relative to the fixed comb.

2.2. Capacitive electrostatic force

Actually, the energy stored between any two conductors is the capacitance energy W; it can be expressed as

$$W = \frac{1}{2} C U^2 \tag{6}$$

where C is the capacitance between two conductors and U is the voltage between the conductors.

If the charge Q between conductors is constant, the conductor should be an isolated system that is not connected to the external power source. The work of the field force can only come from the decrease of the electric field energy, that is:

$$F_n = -\frac{\partial W}{\partial n} = -\frac{1}{2} \frac{\partial}{\partial n} \left(\frac{1}{C}\right) Q^2 = \frac{1}{2} \frac{\partial C}{\partial n} \frac{Q^2}{C^2} = \frac{1}{2} \frac{\partial C}{\partial n} U^2 \tag{7}$$

where n is the relative motion direction coordinates between two conductors; if the voltage U between the conductor is constant, the external power source must be added. When there is an external power source, according to the previous analysis, the work done by the electric field force should be equal to the increase of the electric field energy, that is:

$$F_n = \frac{\partial W}{\partial n} = \frac{1}{2}\frac{\partial C}{\partial n}U^2 \tag{8}$$

Although it looks like a symbol is different, the final form of the formula is the same. For a more general case, when the voltage or charge is variable, the electrostatic force should be expressed as

$$F_n = \frac{\partial}{\partial n}\left(\frac{1}{2}CU^2\right) \text{or}\, F_n = \frac{\partial}{\partial n}\left(\frac{1}{2}\frac{Q^2}{C}\right) \tag{9}$$

According to Eq. (1), the capacitance of the variable capacitor structure shown in **Figure 6** is

$$\mathrm{C(t)} = \frac{C_1(t)C_2}{C_1(t) + C_2} = \frac{\varepsilon_0 w l(t)}{g(t) + {}^{d}/_{\varepsilon_r}} \tag{10}$$

where $\varepsilon_r = \varepsilon/\varepsilon_0$ is the relative dielectric constant of the electrets, w is the width (depth) of the comb, $l(t) = l_0 - x(t)$ is the overlap length between the movable comb and the fixed comb, and $g(t) = g_0 + y(t)$ is the initial distance between the movable comb and the fixed comb. According to the principle of energy derivation, the change of capacitance energy along a certain direction is the electrostatic force in this direction. When the overlap length $l(t)$ between the upper electrode and the electret changes, the electrostatic force between the upper electrode and the electret can be expressed as

$$F_x = \frac{d}{dx}(W) = \frac{d}{dx}\left(\frac{1}{2}\frac{Q_C^2(x)}{C(x)}\right) \text{or}\, F_x = \frac{d}{dx}(W) = \frac{d}{dx}\left(\frac{1}{2}C(x)U_C(x)^2\right) \tag{11}$$

When the gap $g(t)$ between the upper electrode and the electret changes, the electrostatic force between the upper electrode and the electret can be expressed as

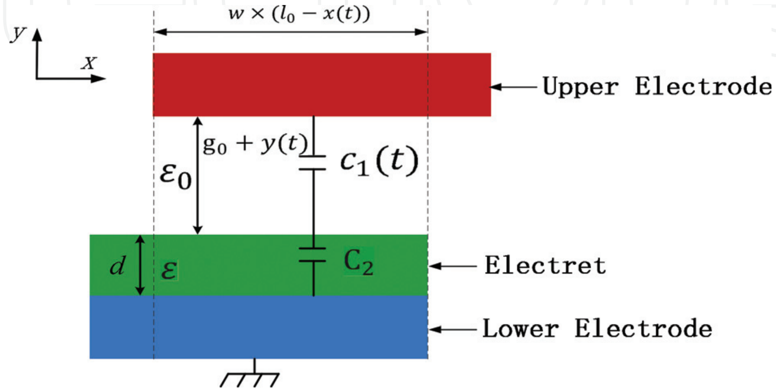

Figure 6. Variable capacitance model.

$$F_y = \frac{d}{dy}(W) = \frac{d}{dy}\left(\frac{1}{2}\frac{Q_C^2(y)}{C(y)}\right) \text{or} \, F_y = \frac{d}{dy}(W) = \frac{d}{dy}\left(\frac{1}{2}C(y)U_C(y)^2\right) \tag{12}$$

where $U_C(n)$ is the voltage between the upper and lower electrodes of the capacitor, $Q_C(n)$ is the amount of charge stored on the upper electrode of the capacitor, and n is the movement direction of the upper electrode of the capacitor relative to the electret or the lower electrode. Electrostatic force changes along the direction of the overlapping electrodes when n is x direction, and electrostatic force changes along the direction of the pitch when n is y direction.

2.3. Electrostatic harvesting mechanism

Although the electrostatic harvesting is based on the environmental forces to change the capacitance and then converts into charge or voltage changes to achieve energy harvesting, there are some mechanism differences for the constant charge mode or constant voltage mode.

2.3.1. Electret-free electrostatic harvester

A. Constant charge work mode

The constant charge work mode is shown in a light-colored (blue) area of **Figure 7**, which indicates that charges are continually injected into the variable capacitor using an external power source (battery, charged capacitor, etc.) until the charge on both ends of the variable capacitor reaches the maximum Q_{cst} when the capacitance of the variable capacitor reaches the maximum $C_{\max}$, and the voltage of the variable capacitor is $U_{\min}$ (Apoint), and then the electromechanical transformation will start. During the energy conversion stage, the charge Q_{cst} remains unchanged, and the variable capacitance changes under the action of external force and gradually decreases from the maximum value until the variable capacitance reaches the minimum value $C_{\min}$. At the same time, the voltage U increases until the voltage reaches the maximum value $U_{\max}$ (Bpoint). After that, through the circuit control, the charge in the variable capacitor is transferred to the external charge storage element until the voltage is zero and the charge is cleared; returning to the O point, an energy conversion is completed and enters the next harvesting cycle. The output electrical energy converted from mechanical energy at a harvesting cycle is

$$E = \frac{1}{2}Q_{cst}^2\left(\frac{1}{C_{\min}} - \frac{1}{C_{\max}}\right) \tag{13}$$

In order to keep the charge of the external power supply (battery, charged capacitor, etc.) from loss, it is usually controlled by the circuit switch to transfer the charge in the charge storage element back to the external power supply at the same time as the variable capacitance changes.

b. Constant voltage work mode

Constant voltage work mode is shown in **Figure 7** dark (red) area, where it also indicates that the electrostatic harvester starts to harvest when variable capacitance reaches the maximum $C_{\max}$.

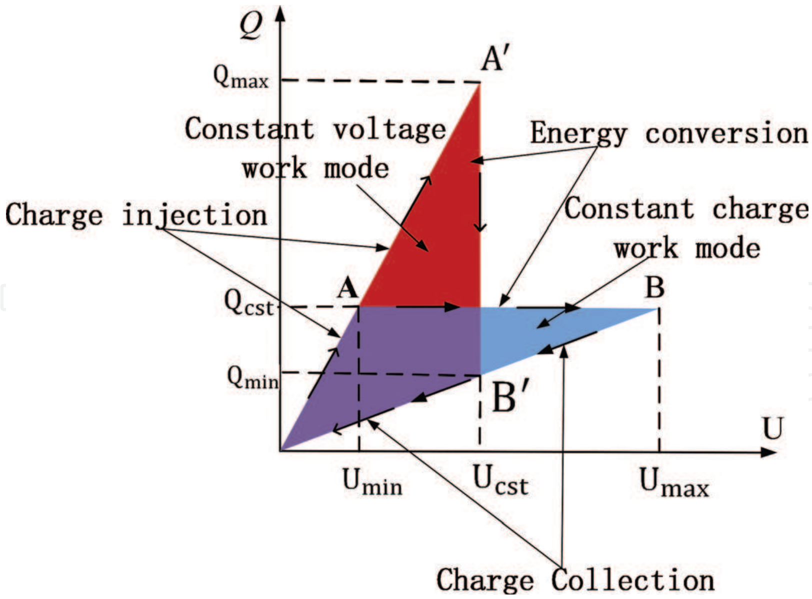

Figure 7. Basic energy conversion cycle of the electret-free electrostatic harvester.

The variable capacitor is charged up to a certain voltage U_{cst} (A' point) by an external power supply (battery, charged capacitor, etc.), the amount of charge stored in the capacitor reaches its maximum $Q_{\max}$, and thereafter the voltage U_{cst} remains constant throughout the electromechanical conversion. As the voltage across the variable capacitor is constant, when the variable capacitance decreases with the external force, the amount of charge stored in the variable capacitor decreases, and the reduced amount of charge generates current through the external circuit loop. When the variable capacitor reaches its minimum value $C_{\min}$ (B' point), the residual charge $Q_{\min}$ continues to be transferred to the external circuit in a reducing voltage manner until the voltage and charge are both equal to zero. At this point, one energy conversion process is completed. The electrical energy converted from mechanical energy in a work cycle is

$$E = \frac{1}{2} U_{cst}^2 (C_{\max} - C_{\min}) \tag{14}$$

For electret-free electrostatic harvester, whether it works on the constant charge mode or constant voltage mode, an external power supply (battery, charged capacitor) is required to supply charge for variable capacitance either before the start of electromechanical conversion or at the first energy cycle. Whether in constant charge mode or constant voltage mode of operation, variable capacitance provides charge. Obviously, this is a drawback of the electret-free electrostatic harvester.

2.3.2. *The electrostatic harvester based on the electret*

The electrostatic harvester based on the electret can directly convert the vibration energy into electric energy without requiring external power to charge and discharge the variable capacitor, thus simplifying the control circuit.

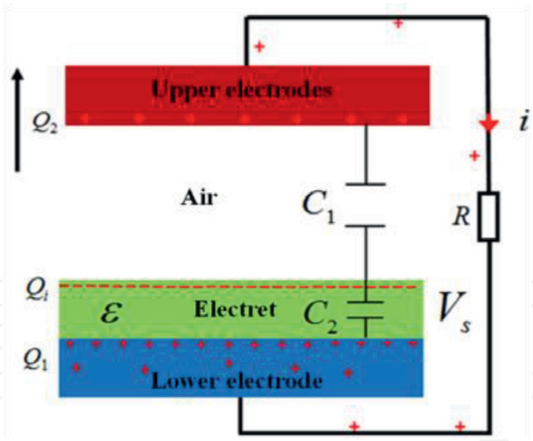

Figure 8. Energy conversion model of electret electrostatic harvester.

In the electret electrostatic harvester, mechanical energy is also converted into electrical energy by the change of the capacitance structure (**Figure 8**). The electret is attached on the surface of the lower electrode. The electrets are separated from the upper electrode by air, and the upper and lower electrodes are connected together by a resistor. According to the electrostatic induction and the charge conservation, the upper and lower electrodes will induct the same polarity charge as the charge polarity of the electret. Q_1 indicates the amount of charge induced by the lower electrode, Q_2 indicates the amount of charge induced by the upper electrode, Q_i indicates the amount of charge in electret, and it is equal to the sum of Q_1 and Q_2. When the upper electrode moves relative to the electret and the lower electrode under the action of external force, the capacitance between the upper electrode and the electret changes, resulting in the redistribution of the charges carried by the upper electrode and the lower electrode. When the upper electrode is close to the electret under the action of external force, the capacitance formed between the upper electrode and the electret will increase. The amount of charge in the upper plate increases, and the amount of charge in the lower plate decreases (**Figure 9a**). When the upper electrode is far away from the electret under the action of external force, the capacitance formed between the upper electrode and the electret will be reduced. The amount of charge in the upper plate decreases, and the amount of charge in the lower plate increases (**Figure 9b**). When the charge flows in the circuit, the current is produced; the voltage across the resistor is generated, so the mechanical energy is converted into electric energy.

2.3.3. Equivalent circuit model

The electrostatic harvesting unit of the electrostatic harvester based on the electret can be equivalent to a series connection of a voltage source and a variable capacitor. **Figure 10** shows the circuit formed by the electrostatic harvesting unit and the load resistor.

When the electrostatic harvesting unit is connected to the load resistor to form a loop, according to Kirchhoff's law, there is $iR = R\frac{dQ_2}{dt} = U = V_s - U_c = V_s - \frac{Q_2}{C(t)}$, then

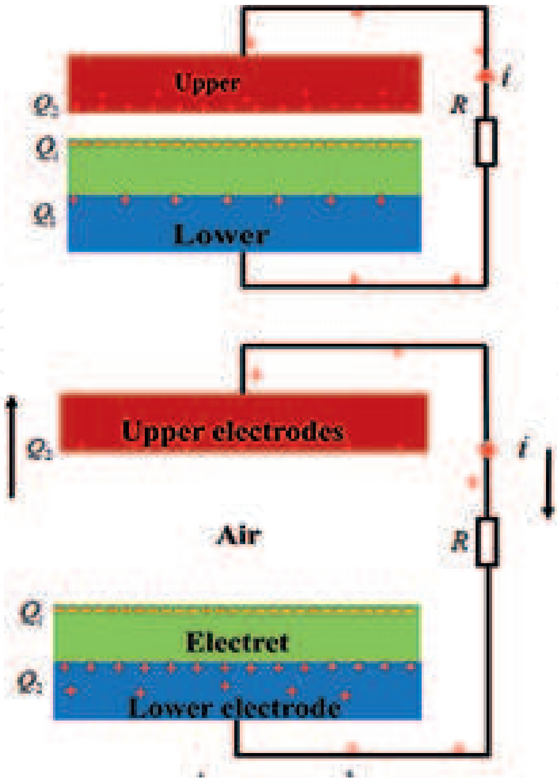

Figure 9. Charge cycle model.

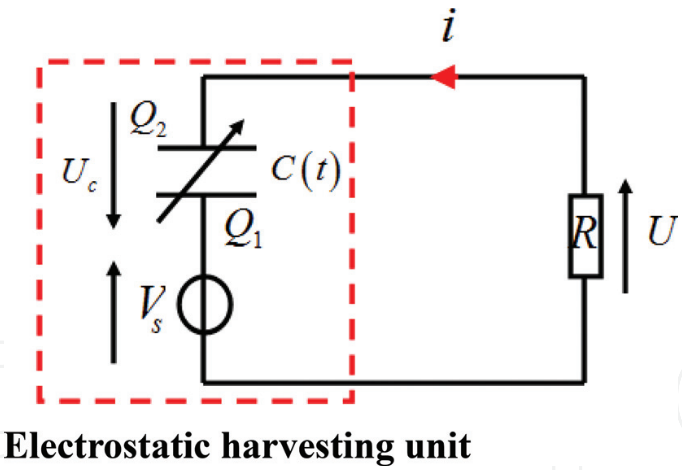

Figure 10. The circuit formed by the electrostatic harvesting unit and the load resistance.

$$\frac{dQ_2}{dt} = \frac{V_s}{R} - \frac{Q_2}{RC(t)} \tag{15}$$

where V_s is the surface potential of the electrets, $C(t)$ represents the capacitance value of the variable capacitor, R represents the load resistance, U represents the voltage across the load resistance, U_c represents the voltage across the capacitor, and Q_2 represents the charge carried by the upper electrode of the variable capacitor.

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2.4. The cantilever electrostatic harvester based on electret

In 2011, Boisseau proposed a cantilever electret electrostatic harvester structure based on a -pitch-tuning planar capacitive structure (**Figure 11**). This structure better illustrates the working mechanism of the electret electrostatic harvester and gives its theoretical model. The electret electrostatic harvester consists of a vibrating unit and an electrostatic harvesting unit. The vibration unit is a second-order vibration system consisting of a cantilever beam and a mass. The electrostatic harvesting unit consists of a variable capacitor and a load resistor. The upper surface of the free end of the cantilever is fixedly connected with the mass, and the lower surface of the free end of the cantilever is covered with a layer of electrode as upper electrode of the variable capacitor. The structure of the pitch-tuning planar capacitor is shown in **Figure 8**, Q_i is the amount of charge carried by the electret, Q_1 is the amount of charge induced by the lower electrode, Q_2 is the amount of charge induced by the upper electrode, and Q_i is equal to the sum of Q_1 and Q_2. Under the action of external acceleration, the space between the free end of the cantilever and the electret will change. As a result, the capacitance of the variable capacitor will change, and the charge between the upper and lower electrodes will be redistributed. There will be a charge flow in the circuit and the electric current formed. So, a part of the mechanical energy excited by the vibration of the external environment is converted into electric energy. The equivalent circuit model is shown in **Figure 10**.

The kinetic equation and electrical equation of a cantilever electret electrostatic harvester are as follows (**Figure 12**):

$$\begin{cases} m\ddot{x} + c\dot{x} + kx - F_{elec} - mg = m\ddot{y} \\ \dfrac{dQ_2}{dt} = \dfrac{V_s}{R} - \dfrac{Q_2}{RC(t)} \end{cases} \tag{16}$$

where the capacitance of the variable capacitor is

$$C(t) = \frac{\varepsilon_0 w \lambda}{g_0 + {}^{d}/_{\varepsilon_r} - x(t)} \tag{17}$$

where $\ddot{y}$ represents the external excitation acceleration, m represents the mass of the mass, c represents the damping coefficient of the vibrating unit, k represents the stiffness of the

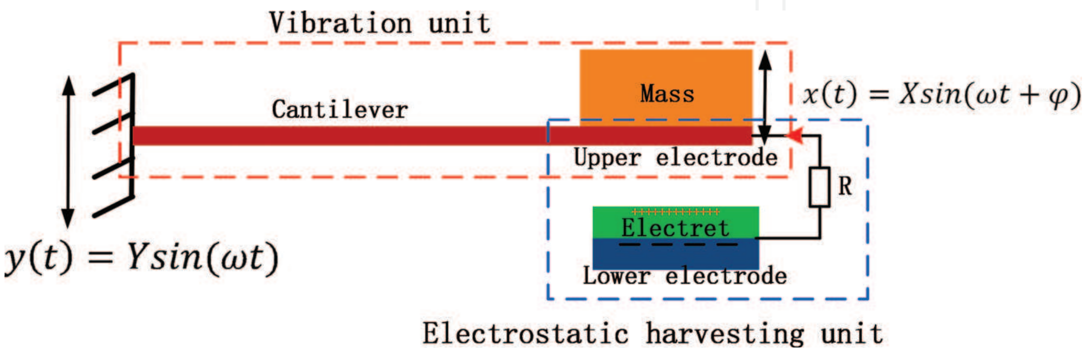

Figure 11. The schematic of cantilever electrostatic harvester based on electret.

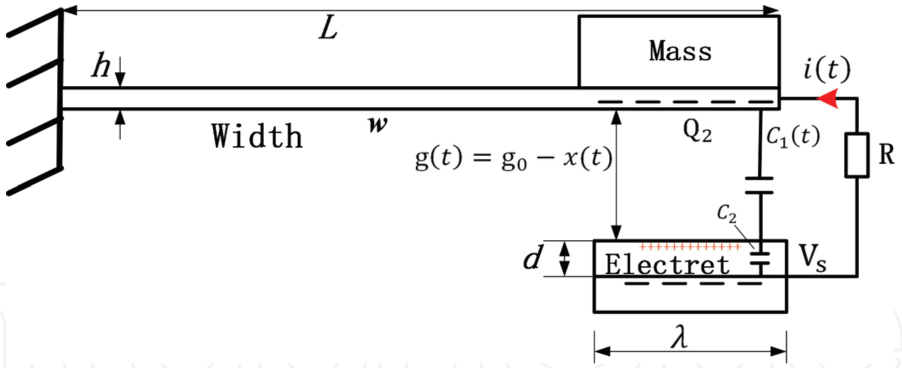

Figure 12. The parameter schematic of cantilever electrostatic harvester based on electret.

vibrating unit, Q_2 represents the amount of charge induced on the upper electrode of variable capacitor, V_s represents the electret surface potential (it keep constant during the entire harvesting process), R represents the load resistance, w represents the width of the electrode, λ represents the length of the electrode, g_0 represents the initial spacing between the upper electrode and the electret, d represents the thickness of the electret, ε_r represents the relative permittivity of the electret, and $x(\mathrm{t})$ is displacement of free end of cantilever under the action of external vibration. The instantaneous power at both ends of the load resistance is given by

$$P(t) = \frac{U^2}{R} = \frac{1}{R}\left(V_s - \frac{Q_2}{C(t)}\right)^2 \tag{18}$$

From Eq. (18), it can be seen that the electrical output of the electrostatic harvesting unit will affect the vibration response of the vibrating unit due to the electromechanical coupling characteristics of system, which in turn changes the electrical output characteristics of the harvesting unit. Since it is difficult to obtain the solution of the system of Eq. (18) by analytical method, it can usually be analyzed by simulation software such as Simulink. The Simulink simulation model is shown in **Figure 13**.

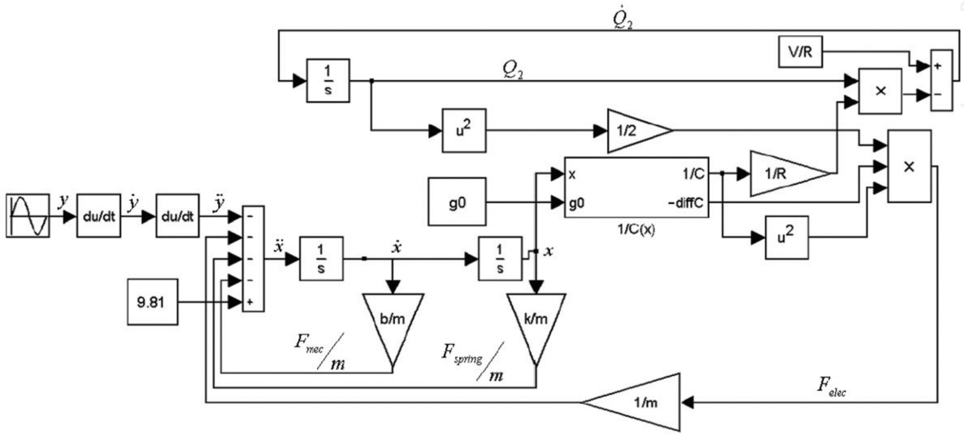

Figure 13. The Simulink model of cantilever electrostatic harvester based on electret.

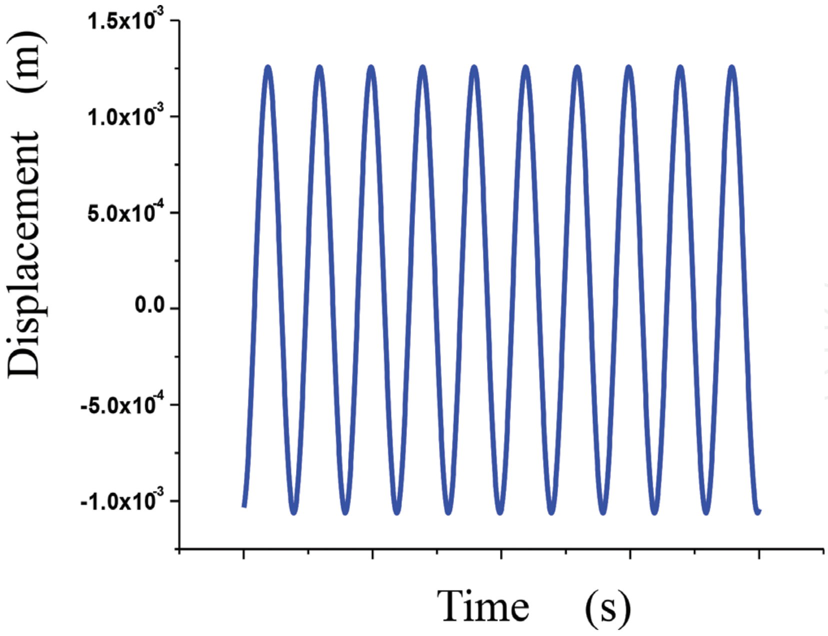

Figure 14. Vibration displacement of cantilever free end.

When an external sinusoidal excitation in which the frequency is 50 Hz and the amplitude is 1.5 m/s^2 is applied to the vibrating unit, the vibration displacement at the free end of the cantilever is shown in **Figure 14**, and **Figure 15** shows the current varies with time in the circuit. When the capacitance reaches the minimum and maximum values, current direction changes. **Figure 16** shows the voltage across the load resistance varies with time, and the peak voltage can be as high as a few hundred volts. It is found through analysis that the surface potential V_s of the electret, the air gap g_0 of the capacitor, the length λ of the electret, and the load resistance R all affect the output power of the cantilever electret electrostatic harvester.

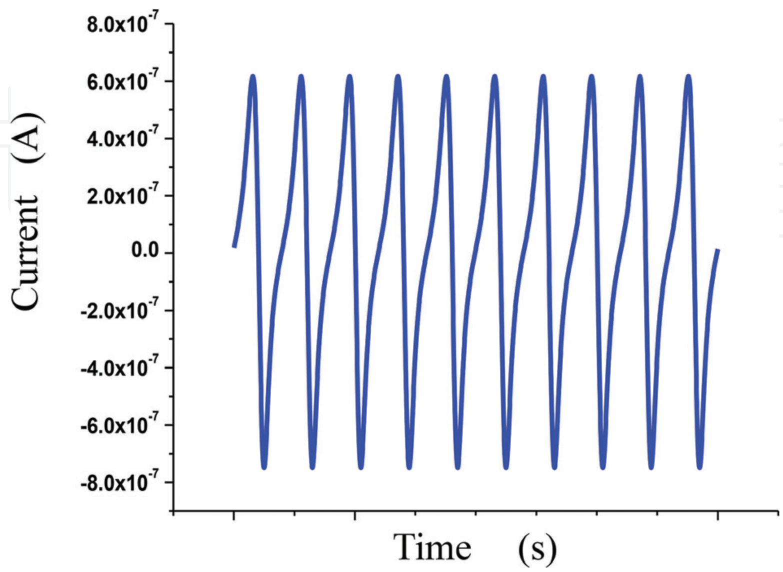

Figure 15. Current varies with time in the circuit.

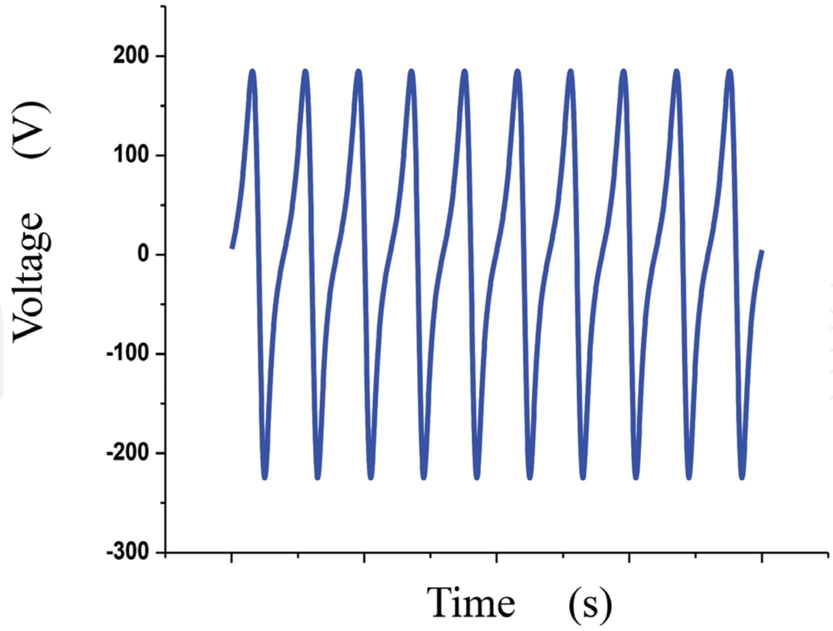

Figure 16. Voltage across the load resistance varies with time.

3. Experimental test on the electret electrostatic harvester output performance

In order to further study the performance of electret electrostatic harvester, a prototype of electrostatic harvester with double-ended fixed-beam electret was fabricated and tested experimentally.

The effects of excitation frequency, air gap, load resistance, and other factors on the output characteristics of the electret electrostatic harvester are tested by the experimental method.

3.1. Effect of excitation frequency on the output of electrostatic harvester

The output of the harvester is related to the excitation frequency. In the acceleration peak of 1.5 harmonic excitation, the output voltage and output power with frequency curve are shown in **Figures 17** and **18**.

The experimental results show that when the initial air gap is 0.2 mm and the acceleration peak is 1.5 m/s^2, the resonant frequency of the electrostatic harvester is 96.2 Hz, the maximum peak-to-peak output voltage is 63.6 V, the corresponding half-power bandwidth is 3.2 Hz, and the maximum output power is 0.054 mW.

3.2. Effect of air gap on the output of electrostatic harvester

The air gap is one of the most important parameters of the electret electrostatic harvester, which plays a key role in the output of the electrostatic harvester.

When the external excitation acceleration peak and the electret surface potential are constant, as shown in **Figure 19**, the output voltage decreases with the increase of air gap. When the air

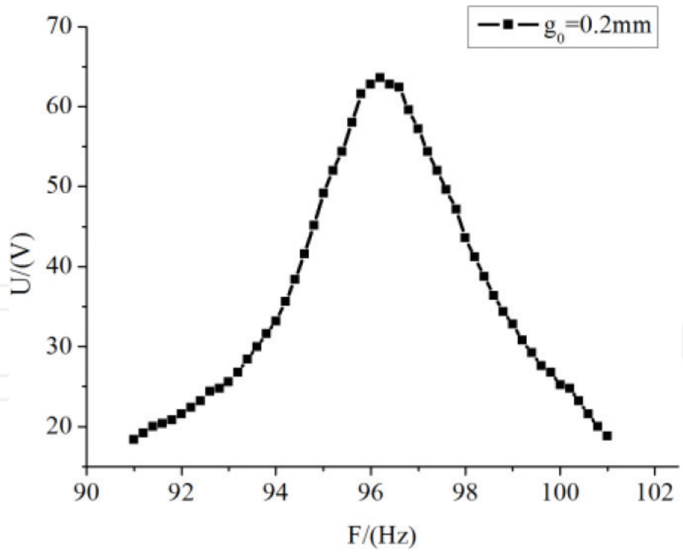

Figure 17. Output voltage with frequency curve.

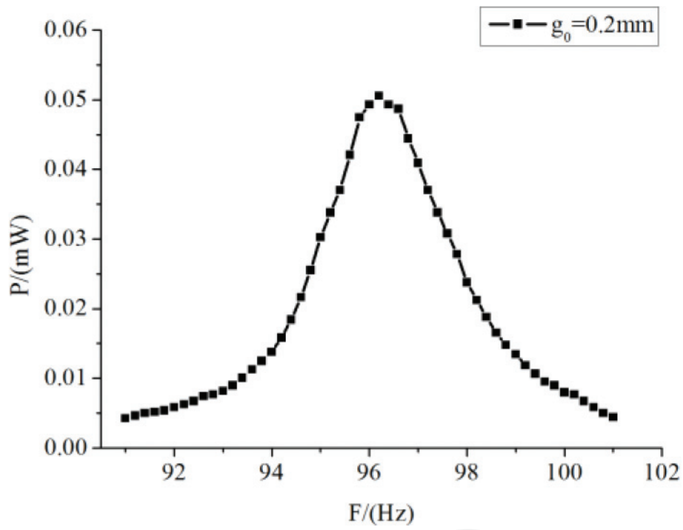

Figure 18. Output power with frequency curve.

gap is 0.15 mm, the peak-to-peak output voltage is 66 V; when the air gap is reduced to 0.5 mm, the output voltage is reduced to 20.8 V.

As shown in **Figure 20**, as the air gap increases, the output power first increases and then decreases. When the gap is 0.2 mm (optimal air gap), the output power reaches a maximum of 0.08 mW. When the air gap increases to 0.5 mm, the output power is reduced to 0.015 mW.

As shown in **Figure 21**, as the air gap decreases, the electrostatic force between the upper and lower plates gradually increases, the soft spring effect increases, and the stiffness coefficient of the spring decreases. As a result, the resonant frequency shifts from 96.8 to 94.8 Hz.

As shown in **Figure 22**, as the air gap decreases, the half-power bandwidth gradually increases. When the air gap is 0.5 mm, the bandwidth is 1.8 Hz, and when the air gap is reduced to 0.15 mm, the bandwidth reaches a maximum of 6 Hz.

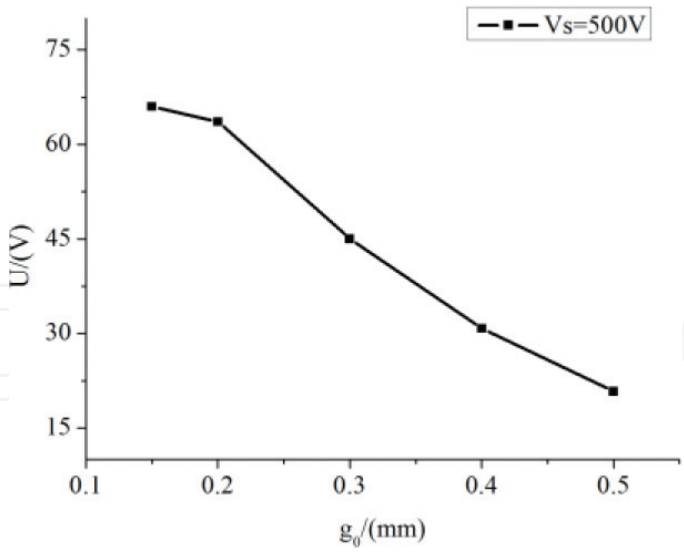

Figure 19. Output voltage with air gap curve.

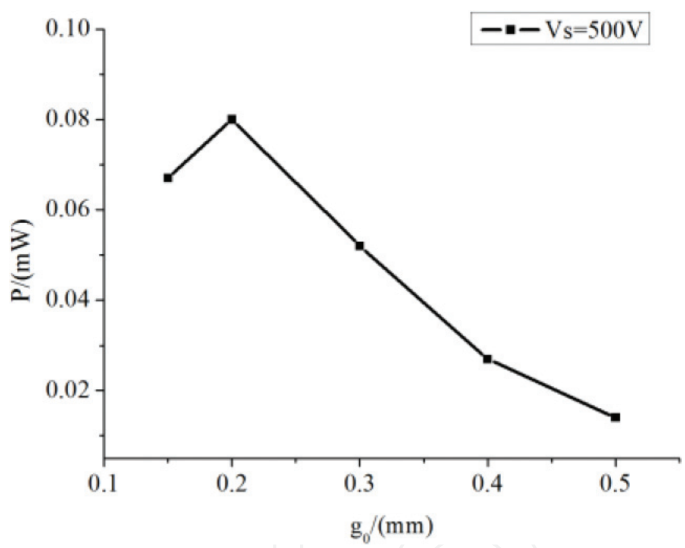

Figure 20. Output power with air gap curve.

3.3. Effect of load on electrostatic harvester output

In addition to the excitation frequency and air gap, the output power of the electrostatic harvester is also related to the external load resistance. The best load test method is as follows:

1. Keeping the acceleration peak of 1.5 m/s^2, the air gap is 0.2 mm.
2. The external load resistance must be connected in series with the oscilloscope during the test.
3. Measuring the output voltage corresponding to different resistances sequentially at the resonance point and plotting the recorded data with Matla (shown in **Figure 23**).

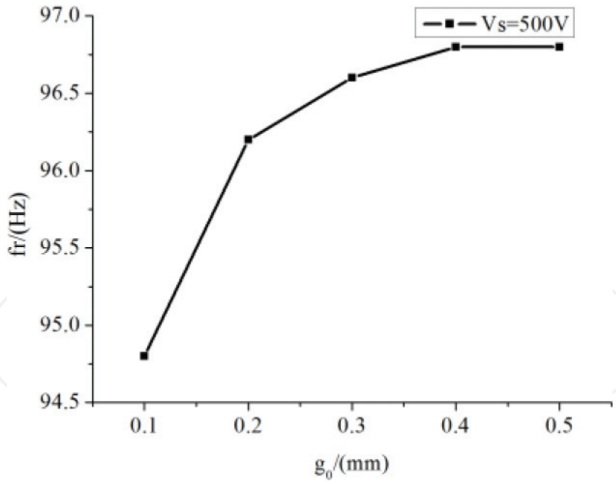

Figure 21. Output power with frequency curve.

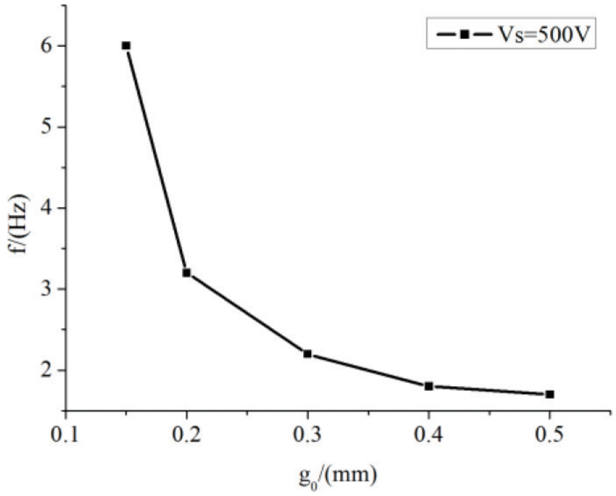

Figure 22. Half power bandwidth with air gap curve.

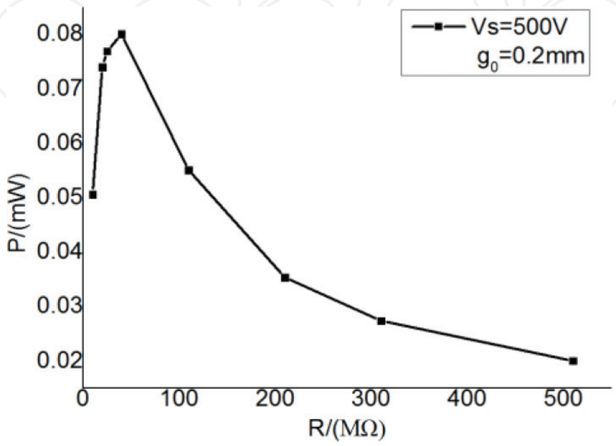

Figure 23. The relationship between load resistance and output power.

As shown in **Figure 23**, as the external load resistance increases, the output power first increases and then decreases. There is a maximum output power of 0.08 mW; the corresponding optimal load is 40 MΩ.

4. Conclusion

Based on the analysis of the basic theory of the electret electrostatic harvester, the basic equations and equivalent analysis model of electret electrostatic harvester are established. Through the experimental tests of electrets electrostatic harvester, it can be seen that the output performance of electret electrostatic harvester is influenced by the parameters, such as excitation frequency, air gap between electrets, and electrode and load resistance and so on. Thus, when designing the electret electrostatic harvester, the influence of some important parameters on the output performance of electrostatic harvester should be considered as much as possible. On the other hand, some microscale effect also should be considered when the MEMS device and the electrostatic energy harvester are integrated design and fabrication. Electrostatic harvesting requires a constant voltage or constant charge condition; it seems that a separate power supply is needed. And it seems contrary to the idea of energy harvesting. However, with the electret material, the material itself can also provide a constant voltage to avoid the use of additional power, which provides an effective way for electrostatic harvesting. Therefore, the electret electrostatic harvesting structure is a kind of ideal energy harvesting method using ambient vibration and can be easily integrated with the MEMS system because of its compatibility with MEMS technology.

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