A review on vibration energy harvesting

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Abstract. Vibration energy capture devices can convert the mechanical energy from ambient source into electrical energy. The captured electrical energy can provide energy for low-power devices such as microelectromechanical systems(MEMS) as a supplement to the power system. Vibration energy has been widely concerned by researchers because of the characteristics of easy access and green. The conversion of mechanical vibration energy into electrical energy can be achieved by electromagnetic, electrostatic, piezoelectric, magnetostrictive, dielectric elastomer and emerging friction nano-types. This paper have discussed some parts of the vibration energy harvesting: collection principle, collection method and the energy storage circuit. At present, the research and design of mechanical vibration energy harvesting structures focus on three aspects: broadening the collection frequency band, collecting dimensions and improving efficiency. Finally, the future direction of energy harvesting research is predicted.

1 Introduction

With the development of the world economy and the increase of the population, society's demand for energy is increasing^[1]. The carbon dioxide produced by burning of oil and coal will exacerbate global warming^[2]. Traditional energy cannot meet the requirements of long-term sustainable development. Hence, countries are urging to develop green energy undertakings. Common green renewable energy sources are: solar, thermal, radio frequency waves(RF), ocean waves, wind and mechanical vibration energy^[3-6]. Some energy densities are shown in Table 1^[7-8]. Vibration is widespread in life. If it has not been collected, it will dissipate sooner or later. Therefore, a lot of research works have been invested.

The common forms of vibration are: mechanical vibration and fluid vibration. The forms of vibration have wind and ocean wave energy^[2,9]. According to the International Renewable Energy Agency data, ocean wave energy development potential is 20,000-80,000 TWh per year, which is twice the global power generation capacity^[10]. After effective development, it can solve 10% of the world's electricity problems. The energy form of fluid vibration has obvious advantages, such as: high energy densities, wide distributions, inexhaustible and less burden on the natural environment. But the shortcomings are also obvious. For example, it is greatly affected by the monsoon, required high operating efficiency and quality of power generation equipment. Meanwhile, it is difficult to operate, maintain and manage. The wind energy or ocean wave energy belong

to the category of high-power or super-power energy. This article mainly discusses the collection of mechanical vibration energy, which belongs to the category of small or micro power collection.

Table 1. Power density of different forms of energy.

Energy Source	Power Density()
Solar(direct sun)	15mW/cm ³
Ocean waves	2-3kW/m ²
Vibrations	10-300mW
Temperature gradient	15 μ W /cm ³ at 10 ⁻² °C gradient
Wind	0.1-0.5kW/m ²

Vibration energy collection is favored by researchers because it can continuously provide energy for low-power wireless sensor networks and microelectronic systems^[11]. The collection principle of most current energy harvesting devices is linear resonance. When the vibration frequency of ambient vibration source is close to the natural frequency of the capture device, the energy conversion efficiency is highest^[12-13]. Once it deviates from the natural frequency, the efficiency of the energy capturing device decreases rapidly^[14]. Therefore, broadening the resonant frequency band of energy capture devices is of great significance to improving the efficiency of energy harvesting. However, there are some disadvantages such as low efficiency of the collection device, not wide frequency band, single collection direction and low output voltage and power in the capture mechanism. Scholars put a lot of vigor into

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broadening the natural frequency of energy capture devices.

Researchers usually introduced some non-linear factors to broaden the frequency band of energy harvesting devices, improve the efficiency of collection and increase the dimension of collection. The reason is non-linear technology can broaden the frequency band of energy harvesting without sacrificing energy density and performance. A commonly used method is to introduce non-linear stiffness through magnetic force to generate a bistable state, which allowed the natural frequency of the mechanism to match the source's lowest-frequency and highest-frequency automatically^[15-16]. As shown in Figure 1.

Figure1. Schematic diagram of bistable cantilever beam^[16]

Figure 2. Flow chart of energy harvesting^[18]

2.1 Methods of vibration energy harvesting

There are several types of devices used to collect vibration energy: piezoelectric, electrostatic, electromagnetic, magnetostrictive and dielectric elastic^[19-23]. Reference[24] showed that in the past ten years, the number of searches for piezoelectric collection devices has remained high level in Web of Science searches. The reason is that the piezoelectric devices have the advantages of high energy conversion efficiency, easy processing, design and integration with MEMS technology.

Reference[17] have proposed a vibration energy harvesting structure based on piezoelectric materials that replaced the concentrated mass with a Z-type beam structure. The introduction of non-linear mass through the Z-type beam structure enabled the energy harvester to concentrate more modal in the low frequency range, broaden the collection frequency band and realize energy collection in three dimensions. The maximum open circuit voltage can reach 16V and the maximum output power can reach 0.18. mW.

2 Vibration energy capture devices

Figure 2 describes the general process of vibration energy harvesting^[18]. It is not only suitable for wireless sensor networks but also for other common energy harvesting methods. First, the energy harvesting device absorbs the mechanical energy of the vibration source and converts it into electrical energy. Then, the energy storage circuit manages and controls the collected electrical energy. Finally, stable power is provided to low-power devices.

2.2 Basic principles of piezoelectric energy harvesting

Figure 3 shows two polarization modes of the piezoelectric transducer: 33 mode and 31 mode^[25]. In the "33" mode, when the piezoelectric material is subjected to longitudinal pressure, the two kinds of charges with opposite polarities are collected on the upper and lower surfaces of the material. In the "31" mode, when the piezoelectric material is stretched laterally, charges will accumulate on the upper and lower surfaces of the material. Reference[26] believes that the electromechanical coupling coefficient of "33" mode is higher than that of "31" mode. Reference [27] believes that the "31" mode is more suitable for collecting environmental vibration sources with lower pressure.

Figure 3. 33 mode and 31 mode

In the circuit model of the piezoelectric energy harvester, Deng Zhiqiang and etc. believe that the piezoelectric element can be regarded as a sinusoidal

alternating current^[28]. In the Figure 4(a), C_{PZT} is super capacitor that stores energy, and R_L is an output resistance.

Figure 4. piezoelectric energy harvester (a) Circuit model (b) Equivalent physical model

The piezoelectric cantilever beam is usually simplified into a physical model as shown in Figure 4(b)^[29]. Where m is the mass of the cantilever beam system, c is the damping coefficient of the system, k is the stiffness coefficient of the system, γ is the displacement of the base, x is the displacement of the cantilever beam's end, C_0 is the energy storage capacitor and R is the output resistance of the system, A is the electromechanical coupling coefficient^[30]. The strain produced by the polarization and vibration of the piezoelectric material is in the direction of axis 3 in Figure 3. Hence, the piezoelectric constitutive equation is:

$$S = E(s - de) \quad (1)$$

$$D = dS + \epsilon e \quad (2)$$

Where S is the mechanical stress of the piezoelectric material, E is the elastic modulus of the piezoelectric material, s is the mechanical strain of the piezoelectric material, d is the piezoelectric constant, D is the electric

displacement, ϵ is the permittivity and e is the electric field strength^[31]. The vibration differential equation corresponding to the piezoelectric cantilever beam is:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) - \alpha U = m\ddot{\gamma}(t) \quad (3)$$

Where U is the output voltage of the system.

2.3 Energy storage circuits

At present, the interface circuits in energy harvester have undergone several generations, from standard energy harvesting circuit (SHE) of the full-wave rectifier bridge mainly composed of ordinary diodes at the beginning, then to the Synchronized charge extraction (SCE) and the synchronous switch harvest on inductor (SSHI) circuit. That development has greatly improved the efficiency of energy collection^[32-37].

The power loss of the energy harvesting circuit system designed by Li Yani etc. is only $1.42 \mu W$ ^[38]. As shown in Figure 5.

Figure 5. Self-powered energy harvesting rectifier controlled by digital switch

With the development of chip manufacturing technology, Semiconductor companies have produced low-power energy harvesting chips. In 2012, Xu Yifan etc. designed an energy harvesting circuit with the LTC3588 energy harvesting chip^[39]. The piezoelectric energy harvesting device converts the collected

mechanical energy into electrical energy. After the quadruple voltage circuit (as shown in Figure 6), the electrical energy is sent to the power management circuit composed of LTC3588. Finally a stable voltage is outputted, which powering low-power sensors. As shown in Figure 7.

Figure 6. The quadruple voltage circuit^[39]

Figure 7. Power management circuit^[39]

Figure 8 is the micro energy harvesting circuit designed by Prijic A etc.^[40] in 2014. The using LTC3108 is a DC/DC converter that integrates ultra-low voltage, booster and power manager. The input voltage of this

circuit can be as low as 20 mV and has a very low quiescent current. Generally, it is used to power low-power sensors.

Figure 9 shows the energy harvesting circuit designed with MAX series chips^[41]. According to the direction of energy transfer, the electric energy is stored in the super capacitor C_3 through the 4 times voltage boost circuit.

Rong Xun etc. designed a micro energy harvesting circuit with low power consumption^[42]. The circuit used the LTC3588-1 power management chip is the core voltage conversion circuit, the LTC4071 charging control chip is charge control circuit and the TPL5100 is timer circuit. In that way, a low-power and micro energy harvesting circuit was built. Experimental results show that the average power consumption of the circuit is 182μW.

2.4 Equipments for prototype experimental

Vibration energy harvesting device prototype test platform experiments usually need to use a set of vibration table (including signal generator, power amplifier, vibration exciter), acceleration sensor, oscilloscope, signal acquisition card and controller (usually a computer).

3 Trends in future research

Vibration energy harvesting technology provides a potential self-powered solution for powering low-power devices. At present, many implementation forms have been proposed according to the principle and design of energy harvesting. But there are still few practical

The function of the circuit module with MAX1795 is voltage regulation, and the function of the circuit module with MAX1811 is energy storage management. Finally, a stable DC voltage is obtained.

application cases. According to the current research results, the future research hotspot trends are as follows:

- (1) Frequency band is an important point of common concern in the field of mechanical vibration energy harvesting. In the future, we can continue to optimize the material's parameters and improve the structure to broaden the natural frequency of the collection device.
- (2) There are few literatures on energy harvesting devices of arbitrary dimensions, which is still to be studied.
- (3) With the emergence of new materials and new types of energy storage management chips, how to miniaturize vibration energy capture devices is still to be studied.

4 Conclusion

This paper makes a review from two aspects: vibration energy collection principle and energy storage management circuit. The ambient vibration source capture technology provides energy for MEMS with the characteristics of long-lasting stability, high efficiency and green, good integration compatibility. The main problem currently facing is how to improve the broadband and high-efficiency energy collection of micro-power, which still has a gap with practical

applications. The concentration of future research on ambient vibration-driven micro power supplies is still broadband, multi-dimensionality, miniaturization and high efficiency.

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