Development of wearable equipment and piezoelectric vibration energy harvest devices

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Abstract. With the continuous development of micro-electro-mechanical system, integrated circuit and wireless communication technology in recent years, piezoelectric vibration energy harvesting technology has been widely used in the power supply system of different scale electromechanical equipment. In particular, it is closely related to the human life wearable devices which shows the urgent demand of micro energy technology. In this paper, the basic principle and common structure of piezoelectric energy harvesting are reviewed. The main research achievements and progress of piezoelectric energy harvesting for wearable devices are analysed, and the challenges and proposed solutions for the piezoelectric energy harvesters based on wearable devices are discussed.

1. Introduction

With the continuous development of micro-electro-mechanical system (MEMS), integrated circuit (IC) and wireless communication technology in recent years, the application of microelectronic devices, micro sensors and portable devices, such as micro systems, has been expanded in many fields, including dressing equipment, environmental control system, human health detection system, and the military security system for its small size and multiple functions [1, 2]. Wearable Electronics are now in the lives of people. It is closely connected to the network society according to the corresponding requirements of consumer groups.

In terms of current use, these devices rely mainly on traditional chemical batteries to provide energy. For example, for the power supply of wearable devices, the conventional batteries mostly used can be categorized into two types: replaceable button battery, and lithium battery. At present, the micro energy harvesting technology is limited in the application in MEMS devices for the following reasons: (1) the big size of batteries not suitable for further miniaturization, (2) the chemical toxic contents inside the battery, and (3) the limited energy supply life[3].

The energy harvesting is the kind of process in which the weak energy absorbed in the environment of an electronic device is converted into a subsequent use of electrical energy. The main micro energy sources in the environment include light, temperature difference, deformation, vibration, radio frequency signals and so on.

The vibration based harvesting technology shows a strong advantage, because it is not affected by external conditions. The vibration energy not only widely exists in the high-speed operation of the electro-mechanical equipment, but also can be collected from body movements, heartbeat and blood flow [1]. In the last decade, it has attracted wide attention from researchers because of its advantages such as high power density (250-330 W/cm³), simple structure, scalability and easy miniaturization [4].

Compared with the static electricity and the electromagnetic energy harvesting devices, the piezoelectric energy harvester has the advantages compatible with MEMS, such as simple structure,
high energy density and long life [5]. In essence, it uses the vibration from the environment, and amplified by a mechanical device, let the external vibration convert into the internal displacement current. In addition, the piezoelectric materials efficiently convert mechanical energy into electrical energy without external output energy, which greatly improves the efficiency and makes the structure of the devices simpler, so that it can be used in different micromachining and volume scales of MEMS devices.

In this research, the piezoelectric energy harvesting (PEH) technology is analysed firstly. Then, the current situation of PEH based on wearable devices is reviewed. Finally, the challenges and development prospect of energy harvesting technology are analysed.

2. Piezoelectric Energy Harvesting

2.1. Piezoelectric Effect
When some dielectric is deformed in certain direction by external force, the polarization phenomenon occurs inside and positive and negative charges are generated on its two relative surfaces simultaneously. When the external force is removed, it returns to the uncharged state, which is called the positive piezoelectric effect. As the direction of force changes, the polarity of the charge changes. On the contrary, when the electric field is applied in the polarization direction, the dielectric will deform. As the electric field is removed, the dielectric deformation disappears. This phenomenon is called the inverse piezoelectric effect [6].

2.2. Constitutive Equation
In the process of PEH, the positive piezoelectric effect is applied, and the constitutive equation[7] is

\[ D_i = d_j T_j + \varepsilon_i^T E_k \]

where \( D \) is the electrical displacement, \( d \) is the piezoelectric stress coefficient, \( T \) is the stress, \( \varepsilon \) is the dielectric constant, and \( E \) is the electric field.

The subscript in the equation (1) refers to the different directions in the coordinate system, and the superscript \( T \) indicates that the electrolyte constant is measured under constant stress. The subscript \( i \) and \( k \) axis, numbered from 1 to 3, similar to the Descartes axis: \( x \), \( y \) and \( z \) axis; In addition to the coordinate axis, subscript \( j \), is defined as the rotation around the axis.

According to the convention, 3 is defined as the polarization direction of the piezoelectric material; Therefore, using the numbers 1 to 6 represent piezoelectric devices work mode, namely the expected direction of mechanical strain and electric field. For example, the piezoelectric sensor is set to run on the \( d_{31} \) mode, that is, if the stress is on the 1 axis, the output is induced by the sensor placed on the 3 electrode.

![Figure 1. The two modes of the piezoelectric energy harvester.](image)

It can be summed up that, \( d_{31} \) is defined as the piezoelectric coefficient of piezoelectric material, which has polarization direction perpendicular to the direction of external force. This coefficient represents the degree of deformation in the width direction caused by electric field in the thickness direction. Likewise, \( d_{33} \) is defined as the piezoelectric coefficient of piezoelectric material, which has
polarization direction parallel to the direction of external force. Figure 1 shows the two modes of the piezoelectric energy harvester. The first half of the formula (1) means that the charge produced in a piezoelectric material is proportional to the stress. Therefore, the PEH devices can be designed to be the form of producing the maximum stress under certain mechanical load.

2.3. Cantilever Beam Structure
Cantilever beam[8] is the most common structure used in the PEH, which can produce the highest average strain at a given input force. Figure 2 shows the schematic view describing the operating principle of a cantilever type piezoelectric energy harvester.

![Figure 2. Schematic of the working principle of a cantilever piezoelectric energy.](image)

The environmental vibration causes the structural vibration of the cantilever base connected to the cantilever beam mass block system. The alternating bending strain is converted to AC voltage during the oscillation process. Frequency matching is one of the most important design considerations in this structure, which requires the accurate coupling of the vibration frequency and the inherent vibration frequency. A cantilever beam usually has a high mechanical quality factor, or a narrow bandwidth. The oscillation frequency drops rapidly with the change of the resonance frequency. Since most environmental vibration is with low frequency, additional mass is added to reduce the resonance frequency of the energy harvester. In addition, the mechanical energy generated by the increased detection quality is stored in the cantilever-mass system to increase the total amount of energy collection.

3. PEH Current Situation
The energy harvesting technology of wearable equipment has been developed in the past ten years. Starner reported on the energy consumed by human activities in daily life [9], as shown in Table 1.

| Activities            | Power/mW | Activities            | Power/mW |
|-----------------------|----------|-----------------------|----------|
| Sleep                 | 81       | Play the violin/piano | 163      |
| Lying                 | 93       | Do housework          | 175      |
| Sit                   | 116      | Do woodwork           | 268      |
| Stand                 | 128      | Walk                  | 407(1609m/h) |
| Talk                  | 128      | Swim                  | 582      |
| Eat                   | 128      | Climb                 | 698      |
| Drive                 | 163      | Run                   | 1630     |

Researchers at MIT have made the piezoelectric shoes in 1998 using lead PZT and polyvinylidene fluoride (PVDF). In 2001, the laboratory made further use of the enhanced PZT double crystal film and improved the performance of the piezoelectric shoe by bending the arch [10]. When the piezoelectric harvester is placed under the foot, the foot exerts a pressure on the PEH, which extends...
to the direction of the F in the d_{31}. This causes the electric field / voltage to be generated from each of the piezoelectric pieces, and the free electrons are driven to the upper and lower surfaces accumulate in the external circuit. In d_{31} mode, open circuit voltage and charge output formula respectively by the following formula \[ [11] \]:

\[
V_{31} = Tg_{31}H
\]

\[
Q_{31} = -TSd_{31}
\]

Where \( G \) and \( D \) are piezoelectric constant and strain constant, respectively, \( T \) is the stress, \( H \) is the thickness of the piezoelectric layer, and \( S \) is the area of the piezoelectric material. It can be concluded from the above formula that the output electric charge is directly proportional to the stress. The area of piezoelectric chip, the piezoelectric strain constant and the voltage output is directly proportional to the piezoelectric voltage coefficient and stress, as shown in figure3\[12\].

![Figure 3. Schematic of the energy harvesting shoes [13].](image)

A TKP (total knee prosthesis) \([14]\) is usually composed of three parts: two elements cover the tibia and femoral epiphysis and the third element is inserted between the tibia and the femur (Figure4(a)). The femoral component, including two condyles, is usually made of stellite (66% cobalt, 28% chromium, 6% molybdenum). The tibial component is a titanium alloy and the articular insert is ultra high molecular weight polyethylene (UHMWPE). The following analysis was conducted using the ZIMMER Knee prosthesis (Figure4(a)). The energy harvesting system is composed of two series of six shaped magnets, and a magnetic axis parallel to the tibial plate, which is located to the special shell of each condyle. A cylindrical coil, parallel to the tibial plate, is placed in a polyethylene insertion pin (Figure 4(b)). The future measurement system will be conveniently placed in the UHMWPE insert, while the electronic circuit for storing and adjusting energy is located in the pin (Figure 4(b))\[15\].

The relative motion of the tibia and femur blade has six degrees of freedom, which is very complex, especially on the sagittal plane. The relative motion of the femur relative to the tibia is not only a simple rotation, but also has a translation movement.

Many researches on the PEH of wearable devices had been presented. Pasquale weaved soft piezoelectric materials and gloves together then collected kinetic energy through the press of gloves \([16]\). Mohajer made a piezoelectric fibre into a belt and passed its pressure to a sensor through the breathing movement of the abdomen \([17]\). Cui combined the piezoelectric materials with the clothing to design the power generation equipment based on cloth, and sewed it on the clothes, which can obtain the better power output after continuous friction \([18]\). Yang et al. designed a PVDF film that adhered to shell shaped polymer film after heat treatment, collecting the energy of human elbow joint \([19]\). Chen studied the energy characteristics of a piezoelectric ceramic implanted in an artificial joint \([20]\). In addition, PEH devices of the arm-movement, the blood vessel beating and the knee joint were studied.
In a word, from the body’s own movement rules of power supply to the portable mobile devices, the key of the energy harvesting is to collect the energy caused by the vibration. The whole structure design is based on the principle of not disturbing the movement of human body and no burden to the human body. The structure of energy harvester tends to miniaturization, and the circuit has been pursuing the path of low threshold, low power consumption and high conversion efficiency.

4. Challenges and Proposed Solutions

The challenges faced by the PEH are mainly as follows:

(1) Bandwidth: At present, most of the designed vibration energy harvester are operating in the resonant mode, and the bandwidth of the half power is usually very small. Because of the phenomenon of frequency drift and resonance in the vibration source, the fixed frequency of harvesting devices which cannot change with the environment has problems. The solution is mainly divided into two aspects. The first is to tune [21] by manual, control system or magnetic force. The second is to increase bandwidth [22] by parallel or series linear cantilever array structure or nonlinear stiffness characteristic structure.

(2) CMOS compatibility: The CMOS compatible MEMS process allows sensors to be manufactured, where mechanical and electrical components are made on the same substrate. The interconnection between mechanical and electrical parts is replaced by wire micro-processing and bonding, which increases reliability and reduces parasitism. However, the current PEH devices are rarely compatible with CMOS. The key to a monolithic device is to develop a CMOS compatible process so that it makes mechanical components without destroying electronic circuits. At present, there are three kinds of the existing methods. The first is the integration of body temperature and process of [23] bond in silicon based on PZT; The second is the process of [24] using zinc oxide (ZnO) or aluminum nitride(AlN) deposition; The third is the use of piezoelectric polymers, such as using the fluoride three fluorine ethylene copolymer (PVDF-TrFE) to make the CMOS-compatible energy harvester [25].

(3) Biocompatibility: Biocompatibility is crucial to wearable devices. The application of implantable medical device (IMD) is very promising, and the most important consideration is to use the biocompatibility of the material. For example, the most commonly used piezoelectric material PZT is not suitable for being implanted into the human body because of its high lead content. Therefore, the selection of lead-free piezoelectric materials is the research direction of IMD. Alternative materials have the following three kinds: The first is potassium sodium niobate (KNN), similar to PZT [26]; the second is implanted flexible equipment on the polyimide [27] deposited AlN thin films; the third is a kind of polymer based on PVDF with high biocompatibility and flexibility [28].
5. Summary
PEH draws great interests because of its high power output density, simple external circuit and flexible extensibility. Despite the considerable progress in the researches and projects, there are still many new problems to be solved. At present, the PEH of wearable equipment has not been commercialized successfully. It is believed that with the further research of piezoelectric materials and better optimization of piezoelectric structures, the practicability and industrialization of wearable piezoelectric vibration energy harvesting devices will be realized in the near future.

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