Technology of Vibration Energy Harvester and Its Application in Vertical Axis Wind Turbine

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Abstract. With the continuous development of mechanical design theory, materials and machining technology, the energy utilization rate of traditional machinery has been approaching the limit. The exhaustion of energy forces mechanical designers to make breakthroughs in the efficient use of energy. Therefore, the technology of energy harvester based on mechanical vibration has been well developed. Based on piezoelectric, electromagnetic, electrostatic, piezoelectric-electromagnetic coupling, and four types of vibration energy harvesting technologies principle and the typical research achievements, systematic analysis of various kinds of vibration energy harvesting technologies features, development and application of the technical difficulties and constraints, the last small Vertical axis wind turbine, for example, analysis of vibration energy harvesting technologies applied in the actual mechanical feasibility and implementation scheme, thus provided for the research and application of vibration energy harvesting equipment development direction and technical guidance.

1. Introduction
Humans have been using fossil fuels for a long time. Especially since the first industrial revolution, fossil energy has become the most important energy to promote the development of human civilization, and cannot be replaced. In recent years, with the continuous depletion of fossil energy and the environmental damage caused by its use, researchers are trying to find various ways to break through the energy barrier. However, since the emergence of heat engine, the pursuit of mechanical efficiency has never stopped, for more than 200 years, the mechanical efficiency of traditional machinery has reached the limit. This makes people have to find new alternative energy or make new breakthroughs in energy utilization. In this context, a kind of energy harvester Technology that collects unused energy in the environment and converts it into electricity that can be directly used [1] has attracted people's attention and was rated as the top ten emerging technologies that changed the world by MIT Technology Review in 2003.

Energy loss is the most important factor causing the low energy utilization rate of the mechanical system. Take the vertical axis wind turbine as an example, the transmission system can consume 20% of the transferred energy, and the total energy consumed by the generator can even be as high as 30% of the total energy input to the generator when the mechanical energy is converted into electrical energy [2]. The energy lost in the necessary process of wind energy conversion is mainly consumed in the form of vibration and friction, resulting in the fan efficiency far below the theoretical value.
Previous studies have shown that energy harvester technology can convert vibration energy into electrical energy. Therefore, the application of energy harvester technology to transform the energy of vibration loss can effectively improve the mechanical efficiency. Preliminary progress has been made in the research of Micro Electro Mechanical Systems [3] and wearable devices [4] energy harvester power supply. Coupled with the breakthrough development of material science and advanced processing and manufacturing processes in recent years, the energy harvester technology is becoming more and more perfect, the efficiency is gradually improved, and the application scope is constantly expanded. Based on the power generation mechanism, performance characteristics and latest research progress of various vibration energy harvester technologies, this paper analyzes the application basis and adaptive conditions of different energy harvester technologies, and realizes the integration of energy harvester technology and related structures of vertical axis wind turbine, which can effectively improve the low utilization rate of wind energy of vertical axis wind turbine.

2. Vibration energy harvester technology and its basic principles

According to different energy conversion mechanisms, vibration energy harvester technology can be divided into piezoelectric, electromagnetic, electrostatic and piezoelectric-magnetic electromagnetic coupling [5].

The basic principle of piezoelectric vibration energy harvester technology is piezoelectric effect, which is essentially that piezoelectric crystals deform when subjected to mechanical forces, causing relative displacement (off-balance position) of charged particles and changing the total electric dipole moment of piezoelectric crystals [6]. Combining the stress-strain relationship of piezoelectric, metal materials, and through the euler-Bernoulli beam path and the given boundary conditions to solve the cantilever type beamform state function can be the first order modal vibration mode function [7], and the i order vibration mode is deduced, the piezoelectric beam up/down the surface along the length direction of the strain model as shown in type 1.

\[
S(x,t) = (c + h) \lambda_i^2 r_i(t) d \left[ (\cosh \lambda_i x - \cos \lambda_i x) - \frac{A_i^2}{A_{i1}} (\sinh \lambda_i x - \sin \lambda_i x) \right]
\]  

(1)

The relation between normalized strain and x-direction length was obtained by substituting in the materials and geometric parameters of the piezoelectric vibrator of the single beam, as shown in figure 1. It can be seen that when the length along the x-direction changes, there is always a strain point with opposite signs on both sides. To avoid this phenomenon, Sun Zhilong et al. [8] proposed a piezoelectric vibrator model of segmented electrode multi-cantilever beam as shown in figure 2. When PZT is pasted, it is broken at the strain point where the second bending vibration symbol is opposite. Compared with the continuous electrode configuration, the peak output voltage of the piezoelectric vibrator with segmented electrode configuration is 2.5 times higher than that with continuous electrode configuration.

Figure 1. Relation between normalized strain and x-direction length during second-order bending vibration.
In order to further improve the piezoelectric efficiency, the researchers introduced nonlinear magnetic force on the basis of the original piezoelectric cantilever to improve the power generation efficiency of the energy harvester device through the interaction between magnetic fields. Experimental data show that magnetic force can effectively improve the energy conversion rate of piezoelectric devices, especially in the low-frequency environment [9]. However, no systematic theory has been formed in the study of the influence of the magnitude of the magnetic force on the power generation efficiency of the energy harvester device and the optimal configuration of the magnetic force.

The basic working principle of electromagnetic vibration energy harvester system is Faraday electromagnetic induction law. When the magnetic flux of the closed loop is changed due to external action, the induced electromotive force will be generated in the circuit. Electromagnetic energy harvesting has a lower internal resistance and a larger output current. Compared with piezoelectric vibration energy harvester system, electromagnetic energy harvester has a higher power for medium-sized system [10]. In ordinary machinery, in order to ensure the normal operation of machinery, the deformation and vibration of parts are limited within a certain range. How to use these tiny movements to realize the efficient operation of electromagnetic vibration energy harvester system remains to be further solved.

Electrostatic vibration energy harvesting technology is the working principle of electrostatic effect, the general need to be guided, namely before it starts to work, need to advance the variable capacitor charging, the capacitor from the original voltage difference between the two plate, when the distance between the two plates is changed due to external force, capacitance value changes, external discharge circuit. In this process, the energy stored by the mechanical vibration is converted into electrical energy [11]. Because electrostatic vibration energy harvesting technology is to discharge electricity to the outside world through the change of capacitance, it has a strong sensitivity to low frequency vibration. However, its work efficiency is strongly dependent on material properties, so there are few breakthrough theoretical research results.

As electrostatic vibration energy harvesting technology of a kind of expansion form, friction electric vibration energy harvesting technology is composed of triboelectrification electrostatic effect with the coupling of a new technology of energy harvesting, its basic principle are the two opposite periodic contact and separation of electrical property of friction surface, so that the induced charge through the external load [12]. At present, due to the low generation of electricity generated by friction and the difficulty of charge separation, the related materials are still in the experimental stage. Piezoelectric - electromagnetic coupling vibration energy harvesting technology is based on the original piezoelectric cantilever beam, using permanent magnet to replace the mass of the cantilever beam, and then arranging the coil reasonably in the direction of the magnet movement. The principle of power generation is that when the mass moves under the action of external excitation, the piezoelectric cantilever beam and the coil respectively generate piezoelectric effect and electromagnetic induction, and generate electric energy at the same time. This kind of energy...
harvesting technology is difficult to develop, complex in structure, and has high requirements on machining process. Actual use has certain technical difficulty.

3. Characteristics and common structures of various energy harvesting technologies

The principle of vibration energy harvesting technology is relatively simple, but the actual application of mechanical structure is diverse. In order to further improve the work efficiency and applicability of the vibration energy harvesting device, researchers have developed a large number of efficient structures according to the characteristics and application scenarios of vibration energy harvesting technology with different mechanisms.

The piezoelectric vibration energy harvesting device is not only simple in structure and easy to process, but also has many advantages such as high energy density, small heat generation, no electromagnetic interference and miniaturization and integration [13]. The main application of piezoelectric vibration energy harvesting is piezoelectric plate, which is made of piezoelectric material embedded in the cantilever of the mechanical structure or attached to the deformation of the structure surface, through the mechanical structure deformation to force the piezoelectric effect of piezoelectric crystals. Liu Jianfang et al. [14] proposed a rotating body extrusion power generation structure as shown in Figure 3. The triangular closed area is formed by three fixed piezoelectric plates, and the inner ball squeezes the piezoelectric material plate during rotation to generate electric charge.

![Figure 3. Schematic diagram of a rotating piezoelectric generator.](image)

1. Case 2. Rivet 3. Elastic piece 4. Piezoelectric material 5. Storage circuit 6. Elastic ball 7. Lead

To amplify the deformation and increase the deformation frequency bandwidth of the piezoelectric vibration energy harvester. Yuan t. et al. [15] proposed a circular piezoelectric plate based on nonlinear dynamics (Figure 4). When the load on the piezoelectric plate fluctuates, the circular plate will be excited and the piezoelectric sheet will be bent to generate electric charge. The simulation and experimental results of the circular piezoelectric plate show that the circular plate vibration energy harvester has softening nonlinearity at low excitation level, hardening nonlinearity and softening nonlinearity at high excitation level. This nonlinear phenomenon can be used to broaden the bandwidth of energy acquisition. Wang, F et al. [16] energy harvesting device based on the Lagrange principle of structural mechanics model (figure 5), and then the quality of the energy harvesting device block under the condition of meet the mechanics model through the Elastic steel sheet (ESS) and a pair of quadrilateral-linkage structure (QLS) is connected to the base, realize adjustable stiffness properties, ultra-low frequency stimulation can smoothly enlarged vibration energy, so as to realize the energy harvester of wide frequency band.
The main research direction of electromagnetic energy harvesting device focuses on improving the resilience number and resilience frequency of the permanent magnet in the coil. Dallago et al. [17] proposed a vertical tubular electromagnetic vibration energy harvester (Figure 6). When the vibration occurs, using the principle of mutual repulsion of opposite magnetic poles, the permanent magnet core can move back and forth in the tube. The moving magnetic pole will change the magnetic flux of the coil wound on the outside of the tube, thus generating the induced electromotive force. Seo et al. [18] further improved this structure by adding springs to the original tubular structure (Figure 7), which could effectively improve the frequency of magnet oscillation.
The most outstanding performance characteristic of electrostatic vibration energy harvester system is that it can take advantage of the low frequency vibration in the environment to produce more output power. No major breakthrough has been achieved in either capacitor plate or materials with tribological properties. In addition, complex processing technology is also required. Therefore, manufacturing is difficult and costly. Some achievements have been made in triboelectric energy harvesting device based on electrostatic energy harvester technology. As shown in Figure 8, Y Lu et al. [19] have proposed a flexible electrostatic kinetic energy harvester whose curved shell can better maintain the structural restorative force, allowing PTFE (polytetrafluoroethylene) to contact with the copper sheet for friction and separation.

Piezoelectric and electromagnetic coupling vibration energy harvesting device is usually based on the traditional piezoelectric cantilever beam to increase the electromagnetic energy harvesting structure, so as to improve the efficiency of the system. Since the system contains two types of electricity generation, piezoelectric and electromagnetic, it needs two kinds of circuits to assist in harvesting electric energy, which increases the complexity of the whole system and puts forward higher requirements on the operating environment. As shown in figure 9, Li P [20] et al. proposed a Piezoelectric and electromagnetic coupling energy harvesting device. Under the external excitation, the mass block of the intermediate magnet moves up and down, and the piezoelectric effect occurs on the piezoelectric plate on the cantilever beam. At the same time, the coil below the magnet generates an induced voltage. Experimental data show that the energy harvester efficiency of the hybrid energy harvesting device is 38% higher than that of the piezoelectric device alone and 118% higher than that of the electromagnetic device alone. On this basis, the researchers also developed a variety of piezoelectric and electromagnetic coupled vibration energy harvesting devices by increasing the...
number of cantilever beams to further increase the energy harvester efficiency. Chen Donghong [21] also optimized the geometry of the beam, and obtained the structure of the four-helix beam and the elemental mass measuring block as shown in Figure 10. The structure can effectively expand the energy harvester bandwidth and energy output density of the device.

![Figure 9. Structure diagram of piezoelectric-electromagnetic coupling energy harvester device](image)

**Figure 9.** Structure diagram of piezoelectric-electromagnetic coupling energy harvester device

![Figure 10. Four-helix beam and the elemental mass measuring block vibration energy harvester device](image)

**Figure 10.** Four-helix beam and the elemental mass measuring block vibration energy harvester device

4. **Application analysis of vibration energy harvester technology in vertical axis wind turbine**

Based on the above analysis of the power generation mechanism, characteristics and common structures of the four vibration energy harvester technologies, it can be concluded that the energy harvesting device has many advantages such as diverse structure, wide adaptability and strong operability. Combined with the specific mechanical structure, its energy harvesting efficiency can be fully utilized. As one of the main mechanical systems for wind energy conversion, the mechanical efficiency of vertical axis wind turbine is generally low. Therefore, the application of vibration energy harvester technology to develop a new type of vertical axis fan can further promote the development of the fan industry. Oy S A et al. [22] proposed a small power wind turbine based on piezoelectric power (as shown in Figure 11). The non-balance turbines is rotated by wind turbine to generate vibration, and the vibration energy is recovered by piezoelectric circuit. Although the device is small in size, generates less electricity and is only used for experimental research, it offers a new way to convert wind energy into electricity. Vibration energy harvester technology can not only be used in the local mechanism of the fan to recover lost energy, but also can directly replace the generator.

![Figure 11. A small power wind turbine based on piezoelectric](image)
There are few examples of application of vibration energy harvester technology in vertical axis wind turbine. However, based on the existing energy harvester structure and combined with the characteristics of vertical axis wind turbine, there is a large space for development.

The main form of piezoelectric vibration energy harvester device is cantilever beam. In the vertical axis wind turbine, the cantilever beam structure is mainly applied to the blade support arm of H-type turbine (figure 12).

A more efficient electromagnetic vibration energy harvester with a model structure similar to that of a damper. Theoretically, a damping system with electromagnetic energy harvester function can be realized by adjusting the stiffness coefficient of the spring and cooperating with the structure of permanent magnet piston. In the vertical axis wind turbine, the connection structure between a single blade and a support arm, and the support structure between a wind turbine and a tower, etc., the damping system can not only recover the lost energy, but also improve the operation stability of the turbine.

The application of an electrostatic vibration energy harvester to a vertical axis wind generator is similar to that of a Piezoelectric and electromagnetic because both require the introduction of an auxiliary mechanism. If each blade of H-type turbine is made into an electrode body, another electrode is set on the rotation path of the turbine, during the rotation of the blade, two electrode plates will be close to and separate, thus realizing the electrostatic effect.

In addition, the new materials used in triboelectric vibration energy harvester technology can be used as excellent materials for vertical axis wind turbine blades. As the blades of vertical axis wind turbine rotate alternately through the windward and leeward areas, the external pressure of the blades in the two areas is different. When passing through the windward area, the blade deforms greatly due to the action of wind force. In the leeward region, the wind action decreases and the deformation decreases. Therefore, changes in blade structure can be formed. The deformation of blade can be used to generate electric energy by properly setting up the generating structure of tribological energy harvester.

For the piezoelectric and electromagnetic coupling vibration energy harvester technology, due to its high energy harvester bandwidth and energy output density, in the vertical axis wind turbine application effect is more considerable. The blade of lift type vertical axis wind turbine generator is generally hollow structure with skeleton inside. The middle mass block structure of multi-cantilever beam is generally symmetrical structure with good bearing capacity. Therefore, the internal skeleton of the lift blade can be combined with the spiral beam structure to effectively utilize the vibration energy of the blade. Moreover, it is possible to develop spiral cantilever beams that fit the airfoil shape and are embedded in the blades to form several generating units. This will further increase the efficiency of vibration energy harvesting.

5. Conclusion

From the above analysis of the structural application of vibration energy harvesting technology and the examples of its application in the vertical axis wind turbine, it can be clearly understood that it is of great significance and practical value to make full use of vibration energy harvesting technology to
develop the energy conversion ability of traditional machinery under the severe situation of the world energy shortage.

Moreover, there are many structural types of vibration energy harvesting devices. With the continuous development of material science and machining technology, most vibration energy harvesting devices only in the experimental development stage can be combined with specific mechanical structures to form more efficient mechanical systems together with traditional machinery. Especially in the field of energy development and utilization technology such as vertical axis wind power generation, when it is difficult to make breakthroughs in related structure and control technology, an alternative application of energy harvester technology can inject new vitality into its development.

However, the application of vibration energy harvester technology in vertical axis fan is still in the basic research stage, and there are few practical applications. There are also technical difficulties such as difficult structural design, low energy conversion rate and large impact on the operating environment. My team and I are committed to the exploration of the above issues, with a view to providing more clean electricity for human production and life and realizing another change in energy technology. At the same time, this paper also hopes to provide some ideas and technical references for researchers and technicians who are doing research on vibration energy harvester technology and wind power technology.

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