Wind-Induced Piezoelectric Energy Harvesting Device for Wireless Sensor Node on the Drum of Mine Hoist

G.B. Zhou
School of Information and Electrical Engineering,
China University of Mining & Technology
China

S.X. Xia
School of Information and Electrical Engineering
China University of Mining & Technology
China

Z.X. Li
School of Mechanical and Electrical Engineering,
China University of Mining & Technology
China

L.H. Huang
School of Mechanical and Electrical Engineering
China University of Mining & Technology
China

***Abstract*—In the surface stress detection system of the mine hoist machine drum, the wireless sensor nodes placed on the drum need to be powered by a battery. Since the sampling frequency is high and the wireless transmitting and receiving data is enormous, the battery needs to be replaced very frequently. To solve this problem, this paper designed wind-induced piezoelectric energy harvestingx8 device for wireless sensor node on the drum of mine hoist, which can charge the battery by obtaining the energy from the environment. In this paper, the structure of the energy harvesting device was introduced, the working principle of wind-induced piezoelectric energy harvesting device on the drum surface of the mine hoist was analyzed, and the piezoelectric bimorph cantilever beam energy harvesting circuit with ultra-low loss characteristics was designed. Based on these, we conducted several experiments with the wind-induced piezoelectric energy harvesting device. The result indicates that the final storage voltage can reach 4.4V at both ends of C3 in the piezoelectric energy harvesting circuit, which means it is able to charge the lithium ion battery.**

Keywords-energy harvesting; wireless sensor; mine hoist

I. INTRODUCTION

Mine hoist is large and complex mechanical equipment which sets machine, electricity, liquid in one. Bearing the mission of elevating of coal and gangue, lowering material, lifting personnel and equipments, it is widely used in coal mine, metallurgy, nonferrous metal, chemical and other industries. Due to complex geological conditions, time-varying operation environment and other factors, longitudinal, circumferential and radial wellbore deformation or even destruction may happen, which can lead to the deformation of elevator guide rail, followed by the abnormal phenomenon of swing and jammed of the hoisting lifting container system and result in major accidents in serious situation, such as lifting container falling from the rail or falling due to the broken rope. Therefore it is of vital importance to improve the safety and reliability of hoist system.

Zhu Zhencai *et al* [1] invented a hoist drum field detection method and device, which achieved the monitoring of the hoist running state and the diagnosing of faults through the real-time detection of drum stress with a wireless sensor network for stress field detection on the basis of mastering the relationship between the stress distribution on the hoist drum plate and typical faults. However, nodes arranged in the rotary body need to be powered by battery. Due to the high sampling frequency of stress data and enormous wireless transmitting and receiving data, the battery should be replaced frequently. Taking energy from the surrounding environment and improving the life of battery are promising solutions needing to be achieved urgently in this case. Since there is a certain relative velocity between hoist drum and air when the hoist drum is rotating, which will cause the air flow in the rotation direction, it's possible to capture wind energy to power wireless nodes.

At present, the research on micro wind power generation technology is mainly divided into four categories: micro wind turbine generator, micro bellows generator, micro electromagnetic wind generator and wind-induced piezoelectric energy harvesting device. The traditional wind power turbine technology is the most mature and most commonly used, but with the reduction of the size, its power generation efficiency decreases due to more serious influence of bearing friction loss and smaller leaf area [2,3]; micro bellows generator has a higher power output when the wind speed is high(>5.5 m/s), but the power output is much smaller when the wind speed is low(<3.5 m/s)[4]; micro electromagnetic wind generator is reliable and the mechanical damping is small, but in the case of low-wind speed, the generator can't work because of the weight of magnets[5]; wind-induced piezoelectric energy harvesting device is cheap, compact, small, light, easy to install, and sensitive to the low-speed wind, what's more, it has a high efficiency of electromechanical conversion, a low magnetic permeability, and it barely has heat loss[6]. Thus wind-induced piezoelectric energy harvesting technology is most suitable for the automation applications and micro power autonomous sensor system among the four.

Nowadays the conversion from widespread vibration energy and fluid energy to electrical energy by a micro piezoelectric energy harvesting device has been receiving great interest from home and abroad [7]. The research of piezoelectric energy harvesting device involves the selection of piezoelectric material, [8] the design and simulation of device structure, the selection of collection and memory component and the design of vibration mode and circuit, the optimization of efficiency etc. A great many of literatures have reported on the piezoelectric energy harvesting device for collecting wind energy to power wireless nodes [9].

In this paper, combined with the working characteristics of mine hoist, a wind-induced piezoelectric energy harvesting device was designed to collect the wind energy to charge a battery of the stress measuring nodes on the drum surface.

II. STRUCTURE OF THE ENERGY HARVESTING DEVICE

As is shown in figure 1, the wind-induced piezoelectric energy harvesting device is composed of energy collector and energy harvesting circuit. It is noticeable that energy collector applies a structure of piezoelectric bimorph cantilever beam.

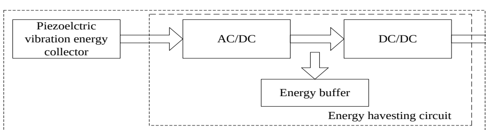

FIGURE I. STRUCTURE OF THE ENERGY HARVESTING DEVICE

III. ENERGY COLLECTOR ON THE DRUM OF MINE HOIST

The location of energy collector on the drum of mine hoist is shown in figure 2. When piezoelectric energy harvesting device rotates with the hoist drum, it has a certain relative speed with the air. As the wind rounds piezoelectric materials, the device structure will generate the alternate shedding vortex in the leeward area, resulting in an alternate vortex-induced force, which causes the vibration of the structure. The above process is what will happen when the piezoelectric material rotates with the hoist drum, namely the Carmen vortex phenomenon. Under the action of the Carmen vortex, piezoelectric material deformation occurs, producing a positive piezoelectric effect, under which the material surface charge generates. Hence the wind energy in the surrounding environment can be converted into electrical energy successfully.

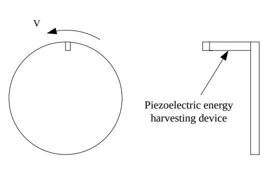

FIGURE II. LOCATION MAP OF THE ENERGY HARVESTING DEVICE ON DRUM CENTER PLATE

As the cantilever support mode can produce the biggest flexure coefficient and compliance coefficient, besides, the vibration frequency of a beam is usually lower than its longitudinal vibration frequency when it works as a rod or its twist vibration frequency when it works as an axis, which can be motivated easily, we choose piezoelectric bimorph cantilever beam structure as energy collector.

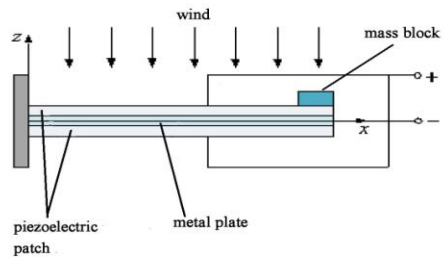

FIGURE III. PIEZOELECTRIC BIMORPH CANTILEVER BEAM

The piezoelectric bimorph energy harvesting device has two types of connection, namely the series and parallel connection. The current output can be double when the piezoelectric patches are in series, whereas the voltage output can be double when the piezoelectric patches are paralleling. Choosing a proper connection type will enable us to achieve a certain topology structure organized with piezoelectric patches which can satisfy the needs of high voltage, high current output and other properties of the piezoelectric power generation device. Since the energy harvesting device in this article is designed for power charging of the low-voltage sensor node, which is easy to reach the demand of voltage, we select a piezoelectric bimorph energy harvesting device with parallel connection mode in order to improve the charging efficiency. The specific structure is shown in figure 3.

IV. ENERGY HARVESTING CIRCUIT SYSTEM

Typically, the power output of the piezoelectric energy harvesting device under the incentive of external environment is extremely low (level μW), and the output voltage can reach (level V) whereas the output current is relatively low (<1 mA), usually in the μA level. Although wireless sensors require less energy, the energy captured by energy harvesting devices alone often fails to power the sensor nodes. Therefore, we must accumulate and store the energy collected by wind-induced piezoelectric energy harvesting circuit to power the wireless sensor nodes at any time. So it is the key to the energy harvesting circuit design to reduce its loss.

A. *Design of Piezoelectric Energy Harvesting Circuit*

In this paper we adopted the piezoelectric bimorph cantilever beam energy harvesting device as the power source of the system, which can output energy sustainably, but the power was insufficient. Lithium ion battery output power is higher, but it stores less energy, so it can work as a power buffer to output power when needed, and it can continuously receive charge from the energy harvesting circuit at other time. Energy harvesting device, lithium ion battery and wireless sensor load has different voltage and current characteristics. The piezoelectric transducing element output power is relatively low, and its voltage is alternating, besides, it can be unstable. The minimum discharge voltage of lithium ion battery is 2.7V, and the highest charging voltage is around 4.2V. Over fully discharge voltage or fully charge voltage will damage the battery which causes a substantial reduction in battery performance. On the other hand, since the voltage required for wireless sensor load is usually a steady DC voltage, the load may not work properly if the input voltage variation exceeds 0.25V.

B. Simulation Analysis of Piezoelectric Energy Harvesting Circuit

In order to analyze the process of energy harvesting circuit regulating output voltage and storing it, which is collected by the piezoelectric cantilever beam energy harvesting device, we adopted the LTspice IV software to simulate the input voltage Vin of the buck regulator, the output signal voltage Vout of piezoelectric energy harvesting circuit and the anode voltage of the battery.

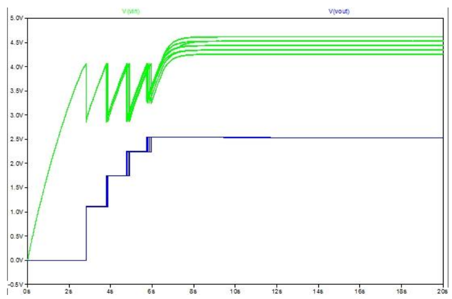

FIGURE IV. RESULTS OF VOLTAGE VIN AND OUTPUT VOLTAGE VOUT

We used the sinusoidal signal to substitute for the input voltage of piezoelectric bimorph energy harvesting device. Under its excitation, we got the vibration of Vin terminal voltage and output voltage signal Vout during the simulation time set beforehand, as is shown in figure 4. The output voltage Vout remained in 0 V at the beginning, and it started to generate a voltage output signal until voltage of Vin terminal reached about 4V.

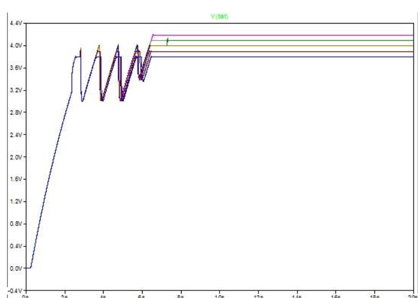

FIGURE V. RESULT OF POSITIVE VOLTAGE FOR SERIES BATTERY

The simulation result of anode voltage of the battery is shown in figure 5, and it could be found that the anode voltage of the battery were stable in 4.2V, 4.1V, 4.0V, 3.9V, 3.8V. The charge floating voltage of the piezoelectric energy harvesting circuit was set to 4.2V, since the maximum voltage of the fully charged battery can reach 4.2V. During the charging process, the rising temperature of the lithium ion battery will result in resistance change of the temperature monitoring thermistor, and then the charging floating voltage changes as well.

V. EXPERIMENTS

Experiments were conducted on the energy harvesting device in this section. The experimental test system was composed of simulation of the hoist drum, piezoelectric cantilever beam energy harvesting device, energy harvesting circuit, data acquisition circuit and wireless transmitting module, wireless receiving module and computer and resistance divider. Among them, the energy harvesting circuit regulate and transport the output energy of the piezoelectric harvesting device, and data acquisition and wireless transmitting module samples the voltage on both ends of the circuit C3. As two dry batteries were adopted to power the data acquisition and wireless transmitting module and their voltage was 3.2 V, while the theoretical voltage on both ends of the energy harvesting circuit was beyond 3.2 V, therefore resistance divider was adopted in this paper to divide the voltage on both ends of circuit C3 before measurement.

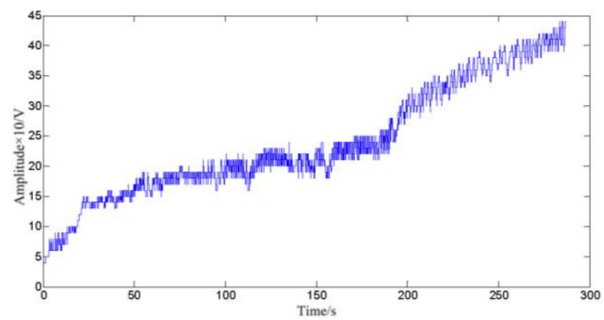

FIGURE VI. OUTPUT OF PIEZOELECTRIC ENERGY HARVESTING DEVICE

As the experimental results showed in Figure 6, the voltage value on both ends of the circuit C3 was fluctuant all the time, but it kept rising in general, which could explain why the output voltage of the piezoelectric energy harvesting device was always being accumulated and stored in the capacitor C3. The ultimate voltage collected by piezoelectric energy harvesting device could reach 4.4 V after being regulated by the energy harvesting circuit, hence charging the lithium ion battery can be realized.

VI. CONCLUSIONS

Aiming at the problem of energy supply of the stress field detection sensor nodes on the mine hoist drum, we designed a kind of wind-induced piezoelectric vibration energy harvesting device. Main work includes:

1) According to the Karman vortex street and the vortex induced resonance principle, the working principle of the wind-induced piezoelectric vibration energy harvesting device was analyzed.

2) Piezoelectric bimorph cantilever beam energy harvesting circuit with ultra low loss characteristic was designed; the input voltage (Vin) of the buck regulator in the piezoelectric energy harvesting circuit, output voltage signal (Vout) of the piezoelectric energy harvesting circuit and the anode voltage of battery were analyzed. The simulation result was consistent with the theoretical result.

3) A simulation experiment system was built, and the wind-induced piezoelectric vibration energy harvesting device was verified by experiment. The ultimate stored voltage collected by piezoelectric energy harvesting circuit could reach 4.4 V, which was possible to charge the lithium ion battery.

ACKNOWLEDGEMENTS

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