Self-powered Triboelectric Nano Vibration Accelerometer Based Wireless Sensor System for Railway State Health Monitoring

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Abstract

Vibration exists everywhere especially in the public railway operation system. The vibration acceleration is the key factor to monitor and evaluate the structure health of the railway equipment. In this paper, a kind of self-powered triboelectric nano vibration accelerometer (TEVA) is presented. A low frequency spring mass vibration model is built to calculate the vibration sensitive performance and the electric output of the TEVA. The prototype of the TEVA is demonstrated and characterized through the railway vibration simulation platform. It has been testified that TEVA can successfully harvest the low frequency vibration energy and convert it to electrical power to achieve the self-powered vibration acceleration monitoring system. The output current and voltage of TEVA are also sensitive to the vibration acceleration from 1.07m/s^2 to 1.25m/s^2 linearly. Hence it can be used as a self-powered nano vibration accelerator for the fault diagnosis. In addition, the generated electricity is used for charging the lithium battery (from 1.5V to 3.1V) which supplies power to the ZigBee module. The experiment shows that the charged battery through TEVA can support the wireless communication between ZigBee modules, with temperature and humidity sensors embedded on it. The temperature and humidity on the train are 22 degree Celsius and 35%RH respectively. Therefore, the vibration energy can be harvested and stored for the power supply of wireless sensor network nodes in the near future.

Keyword: Self-powered vibration accelerometer, Spring Mass Model, triboelectric nanogenerator, wireless sensor, state health monitoring

1. Introduction

With the development of the high speed railway, the safety operation of railway system has attracted more and more attentions. Key equipment of railway system such as bogies and railway tracks need to be inspected to ensure the safety and reliability during the operation^[1]. Information such as using life span and fault classifications derived from the inspection is pretty important for the railway operation safety. Therefore, the state health monitoring (SHM) of key equipment is very necessary. There are a lot of methods for Railway SHM (RSHM), including temperature monitoring, acoustic monitoring and vibration signal monitoring. For example, the wheel brake temperature monitoring will supply feedback to the train driver^[2]. And the air temperature and humidity monitoring of the train carriage will prevent the breakdown of traction power system. Vibration signal analysis has many advantages and suitable for almost every kind of railway key equipment. Besides, the collected vibration signal is easily stored and to process. The processing method is various and the fault diagnosis result is accurate^[3-6]. The vibration signal analysis method has been used widely, a lot of researches has applied this method for the railway key

equipment monitoring and got fruitful results^[7-8].

In recent years, there has been an increasing interest in the adoption of sensing technologies for SHM. And wireless sensor network technology has been introduced into the RSHM to improve the monitoring performance^[9]. Wireless sensor network has the potential to have a great impact on this field, including reducing the cost, increasing density of data collected from the given research object^[10], thus increasing the spread of RSHM systems. A large amount of sensors are installed in trains for the monitoring of objects and form sensor network monitoring system. However, utilization of sensors is still limited because of the poor power supply. Wired energy is not a good option because wires are physically vulnerable and expensive to install and to maintain^[11-12]. In fact, this is the main reason why wireless technology is so important in RSHM applications. Stored energy such as batteries can be used for power supply. However, multiple replacements will be necessary through the lifespan of the monitoring system. That will cost a lot of investment such as time and money. Therefore, energy harvesting^[13-14] from the ambient environment for the sensor power supply is the key for the wireless RSHM system^[15-17].

Not only in the field of railway operation, other industries also face the challenge to solve the power supply of the SHM based on the wireless sensor network. David proposed that the radio-frequency wireless energy transmission system can be used as a possible power solution for sensor nodes of the structural health monitoring system^[18]. Galchev presented a design, fabrication which is used for harvesting the vibration on the bridges. The fabrication can power the wireless sensors used to monitor the structural health bridge^[19-20]. Arms proposed the tuned piezoelectric vibration energy harvesters for Navy aircraft structural health monitoring^[21]. As the literature review shows, although power supply technology for the SHM based on the wireless sensor network has been researched a lot, the power supply for the wireless RSHM system is still unsolved.

During the train operation, it poses a wealth of available ambient energy that can be exploited for power supply of the RSHM systems including, wind, solar and vibrations^[22-24]. Each energy source poses specific challenges which must be overcome. The availability of wind can vary greatly in different places and wind harvesters tend to be in large scale which is not suitable for trains^[25-26]. Solar energy is widely spread and harvested^[27]. But its usage will add extra load and cost to train operations. While there is large amount of kinetic energy generated as the train vibrates in response to the trains passing on the rail. These vibration energy comes in a form that is difficult to harvest, because the train vibrations are low frequency, non-periodic and they have small amplitudes^[28].

The use of triboelectric nanogenerators is a highly effective technology for harvesting mechanical energy^[29-30], such as human walking vibration^[31-32] and kinetic energy^[33]. Recently, Zhu developed a simple and cost-effective approach to fabricate a triboelectric nanogenerator with high electric output^[34]. It can harvest large-scale mechanical energy such as footsteps and rolling wheels. However, owing to the low frequency and small amplitude of the vibration during the train operation, energy harvesting becomes hard for that design. A proper model should be introduced to ensure the efficiency of the energy harvesting.

Therefore, combining the railway operation application, this paper puts forward a low frequency self-powered triboelectric nano vibration accelerometer (TEVA). It provides an unprecedentedly simple and cost effective means for harvesting ambient vibration energy mainly using triboelectric nano materials. By proper design of the spring mass energy harvesting model

and moderate gap design, the designed TEVA can achieve the vibration energy harvesting at a very low frequency. Moreover, the acceleration of the train equipment can be detected through the one-to-one correspondence between the voltage and the acceleration. And this will provide useful data to the RSHM system to carry out fault diagnosis experiments and monitor the state of the train equipment. Compared with the Zhu's pressing model, our model can be spread more widely because it can harvest the vibration energy in low frequency and small amplitude. What's more, no exterior pressure will need for the electricity generation during the harvesting process and have good performance of reliability.

The remaining part of the paper is organized as follows. Section 2 outlines the self-powered TEVA definition and its structure design. And the electricity generation principle of the self-powered TEVA will also be introduced. Section 3 mainly explains the basic theory of the spring mass model. What's more, several simulation experiments via MATLAB are also carried out to assist the design of the TEVA. Section 4 discusses the railway vibration simulation platform and experimental results. Conclusions about the study are drawn in section 5.

2. TEVA Definition and Structure

The diagnosis of the train equipment through vibration signal has become an important method for the safety of train operation. However, due to the unstable power supply and lack of suitable vibration accelerometer, the development of RSHM has been greatly restricted. Therefore in this paper, a kind of nano self-powered TEVA is put forward, which is based on the vibration characteristics of high-speed railway. Because of the high speed and the heavy load of the trains, the rail will generate a large amount of vibration energy when the high-speed trains pass through and the frequency range is beneath 10Hz. The proposed self-powered nano TEVA mainly focuses on the conversion of rail vibration into electricity. The generated power will be used for the power supply of the accelerometer or wireless sensor network nodes.

The self-powered TEVA solves the problem of power supply of the accelerometer. The location of the accelerometer will not be restricted anymore. Thus, the vibration signal of train key equipment will be collected timely and the diagnosis process can be carried out smoothly. Besides, considering the scale and the development tendency of the Chinese train transportation industry, the economic contribution of the saved energy will be considerable.

The self-powered nano TEVA has a layered structure with two substrates, as schemed in Figure 1(a). Poly(methyl methacrylate) (PMMA) is selected as the material for the substrates and vibration mass because of its decent strength, light weight, easy processing, and low cost. PMMA has a high hardness which makes it easy to process. What's more, it can guarantee the rigid contact between the two substrates. To achieve the triboelectric effect, two different film materials need to be introduced for the creation of two different polarities, which will contribute to the electrons transfer between them^[35].

On the lower substrate, a layer of contact electrode is prepared. The contact electrode plays double roles including electrode and contact surface. It consists of an aluminum thin film with aluminum nanolayer adhering to the aluminum film surface. Fig.1(c) shows the uniform distribution of the nanolayer on the Kapton surface. On the upper substrate, a thin film of aluminum is laminated between the substrate and a layer of Kapton nano structure. This film of aluminum is called a back electrode for later reference. The two substrates are connected by four springs installed at the corners of substrates, leaving a narrow gap between the contact electrode and the Kapton nano structure. This gap is a very important parameter to the design of the TEVA

because it has a direct influence on the quantity of the electricity and the sensitivity to vibration signals. The structure of TEVA can be taken as a spring mass model, shown as Fig.1(b). The spring mass model can achieve contacts between two substrates in different speeds or accelerations to generate the electricity and detect sensitive vibration signals. The fabricated TEVA is exhibited in Fig.1(d).

Fig.1: (a):The self-powered TEVA is composed by two triboelectric layers with aluminum and the Kapton nano structure patterned through reactive ion etching method pasted on the PMMA substrates. (b) SEM image of the etching nano structure on the Kapton surface. (c): Four springs (k) are applied to build the spring mass vibration accelerometer system. (d): The fabricated model of TEVA.

The electric energy generation process can be explained by the coupling between triboelectric effect and electrostatic effect^[36-37], as shown in Fig. 2. At the initial position, a separation gap is maintained by four springs, as indicated in Fig.2(a). And suppose that the lower substrate is fixed. When a vibration impact is applied on the upper substrate, the aluminum film and Kapton nano structure are brought into contact. According to the triboelectric series that ranks materials' tendency to gain or lose electrons^[38-39], electrons are injected from the aluminum film into Kapton nano structure, result in surface triboelectric charges (Fig.2(b)). As the vibration impact is withdrawn, the contacting surfaces move apart due to elastic force from four springs. Once a separation forms, the back electrode possess a lower electric potential than contact electrode, producing an electric potential difference. Such a potential difference drives electrons through external loads and screens and positive triboelectric charges on the contact electrode(Fig.2(c)). When the TEVA reverts back to the initial position, positive triboelectric charges on the contact electrode are completely screened, leaving an equal amount of inductive charges on the back electrode (Fig.2(d)). Subsequently, vibration impact once again shortens the separation, producing an electric potential difference with reversed polarity. The electricity quantity is sensitive to the frequency and acceleration of the vibration impact. Therefore, the vibration harvester structure can also be taken as an accelerometer^[40-41].

Fig.2: Working mechanisms of the TEVA (a): Initial state without force applied. (b): Vibration puts the upper substrate in contact with the lower substrate, the triboelectric effect will cause the electrons flow from the contact electrode to the Kapton nano structure. (c): The separation of two substrates causes potential difference between two electrodes and drives electrons from the back electrode to the contact electrode. (d): Original position is recovered with all positive triboelectric charges screened on the back electrode. (e): When the force is reapplied again, electrons are driven back to the back electrode from the contact electrode.

It can be concluded from the principle of the tribo-electrification that the gap between two materials is an important factor for the TEVA to achieve high electricity generation. Because the vibrations are in low frequency, non-periodic and they have small amplitudes, a proper gap between the two triboelectric materials should be designed through the spring mass model. It should guarantee the contact and separation of two materials smoothly. By analyzing the impact of the vibration frequency and vibration amplitude of the vibration source on the gap. Several simulation vibration experiments are carried out based on the spring mass model in Section 3 via MATLAB for choosing the suitable gap between the contact electrode and the Kapton nano structure. The theoretical working curves are also characterized through the simulation result under different frequencies and different accelerations.

3. Theory and simulation

The equivalent model of the TEVA is shown as Fig.1(b), a simplified model has been proposed by Williams and Yates^[42]. The control equation of model is shown as Eq.(1).

$$m\ddot{z} + k\dot{z} + cz = -m\ddot{y} \quad (1)$$

Where m is the equivalent mass, k is the stiffness of the spring, c is the viscous damping coefficient, y is the displacement of base, and z is the relative displacement between the mass and the base. The TEVA works on the vertical contact-separation spring mode to transfer the vibration energy to electric energy.

As the key component of the model, the selection of the spring is very important. The calculation method of the spring stiffness^[43] is shown as Eq.(2).

$$k = Gd^4 / (8D^3n) \quad (2)$$

Where D is the diameter of the spring coil, d is the spring wire diameter, G is the shear modulus, n is the effective number of turns of spring. The equation shows that the spring stiffness is inversely proportional to D^3 and to n , but is proportional to G and to d^4 .

If the spring stiffness is too large, the elastic force is so large that it will prevent two substrates from contacting. If the spring stiffness is too small, the vibration energy will be buffered and the efficiency of the electricity generation will be decreased. After several measurements of voltage under different springs, parameters of the spring is chosen as follows: $D=8\text{mm}$, $d=0.4\text{mm}$, $G=8 \times 10^4 \text{MPa}$, $n=4$. With the above parameters, the value of K equals to 125N/m . In this experimental model, there are four springs between the two substrates, so the total spring stiffness can be taken as $4K$, which equals to 500N/m .

On the other hand, the value of the viscous damping coefficient is another important factor to the TEVA. It will have a direct influence on the response time of the TEVA, which can reflect the sensitivity of the TEVA to the vibration signal. The response time reach to the shortest when the damping ratio is $0.707^{[44]}$ and the calculation method is shown as Eq.(3).

$$\xi = c / (2\sqrt{mk}) \quad (3)$$

Where ξ is the viscous damping ratio, c is the viscous damping coefficient, m is the equivalent mass and k is the stiffness of the spring.

With the viscous damping coefficient, the gap between the two substrates can be calculated out with the Eq.(4)^[45].

$$d = \sqrt[3]{(\mu w^3 l / c) \beta(w/l)} \quad (4)$$

Where μ is the dynamic viscosity of air and $\mu = 1.5 \times 10^{-5}$ when the temperature is 20 degree Celsius. w and l are the wide and the length of the substrate separately and $\beta(w/l) = 0.6$.

According to the Eq.(3) and Eq.(4), the viscous damping coefficient can be figured out. The coefficient value equals to 11.8 and the gap between two substrates is $323\mu\text{m}$. With those parameters, we carry out a simulation via MATLAB. The simulated result show that the vibration amplitude is not large enough to make the two substrates contact because the value of the viscous damping coefficient is too large. Therefore, the value should be decreased to find an optimal balance between the gap and the response amplitude. After several simulations, we find that when c equals to 4, the response amplitude can match the gap ideally, shown as Fig.3. According to the simulation result, the proper gap in this paper equals to $440\mu\text{m}$ to ensure the effective contact of the two substrates. And the designed gap will have a good coverage of the available frequency, shown as Fig.3(c).

Fig.3 Simulation results of the Spring-Mass model by MATLAB: (a): The vibration amplitude response with time(s). (b): The characteristic of the Spring mass model for the phase vs frequency and the amplitude vs frequency. (c): Different amplitude responses under different frequencies when the acceleration is $1.07m/s^2$. (d): Different amplitude responses under different vibration accelerations when the frequency is 6Hz.

The step response time of the TEVA is less than 2 seconds which means the TEVA has a high sensitivity, shown as Fig.3(a). The resonance frequency of the TEVA is 9.5Hz and the gap of the TEVA can be designed according to the amplitude under the resonance frequency. In addition, the phase difference of the TEVA is decreasing with the increase of the frequency, which indicates its stable response performance, shown as Fig.3(b). Amplitude responses under different vibration frequency is shown as Fig.3(c) and the resonance amplitude is about 630um. To find out the relationship between the amplitude and the acceleration, the rail vibration frequency range which is between $1.05m/s^2$ and $1.25 m/s^2$ is selected as the simulation input. And amplitude responses under different vibration accelerations is shown as Fig.3(d). It can be concluded that the amplitude response is increasing with the vibration accelerations. What's more, the amplitude of TEVA is also sensitive to the vibration acceleration from $1.07m/s^2$ to $1.25m/s^2$ linearly. According to the linear relationship, we design the experiment to measure the voltage output under different accelerations, explained in Section 4. The corresponding relationship between the voltage and the acceleration will contribute to the calibration of the TEVA. Thus, the acceleration of rail vibration can be measured by the TEVA. By this method, we can attain the designed purpose of self-powered triboelectric nano vibration accelerometer.

4.Experiments and Results

The oscilloscope (Anglient DSO7104A) is used to measure the voltage output of the TEVA, and the voltage output wave is shown as Figure.4(a). To uncover the relationship between the voltage and the frequency or the acceleration. Two experiments are carried out separately. In the first experiment, the vibration acceleration is fixed and the vibration frequency is increased from 2Hz

to 10Hz with the step of 2Hz. Then, record the peak voltage under different vibration frequencies. In the second experiment, the vibration frequency is fixed and the vibration acceleration is increased from 1.07 m/s^2 to 1.25 m/s^2 with the step of 0.03 m/s^2 . Then record the peak voltage under different vibration accelerations, shown as Fig.4(b) and Fig.4(c) respectively. According to Fig.4(b) and Fig.4(c), the peak voltage is increasing when the vibration frequency or acceleration rises. What's more, the charging process of the battery which supplies the power to the ZigBee module is also recorded under different accelerations, shown as Fig.4(d). From the curve of the charging process, we can also conclude that the charging performance is positive correlated to the acceleration. What's more, Fig.4(d) also shows that with the increase of the battery voltage, the charging performance of the TEVA degrades. The voltage difference between the output voltage and the battery voltage will have direct influence on the charging performance.

Fig.4 (a) When the vibration frequency is 10Hz and the acceleration is 1.25 m/s^2 , the peak voltage of the generated electricity is 88V. (b) When the acceleration is 1.25 m/s^2 , the peak voltage of the generated electricity under different frequencies. (c) When frequencies are 4Hz and 6Hz respectively, the peak voltage of the generated electricity under different accelerations. (d) The charging process of the battery which supplies the power to the ZigBee module.

To simulate the data transfer process of the high speed railway operation. We carry out another experiment based on the vibration experimental platform. The vibration experimental platform for train operation is shown as Fig.5(a-b). It is mainly composed of a vibrator whose model is YSZD, the TEVA, the power supply circuit (as shown in the supporting material), the ZigBee module with two sensors on it, a lithium battery whose nominal voltage is 3V.

The vibrator is for generation of vibration source and the vibrator controller can change the frequency and the acceleration of the vibration. The power supply circuit is designed to ensure a stable voltage output which will be used for charging the battery. Combining the energy harvesting power chip (LTC3588-1), the circuit aims to attain the voltage output about 3.3V. And an oscilloscope (Anglient DSO7104A) is used for the measurement of the voltage under different

vibration frequencies and vibration accelerations. Those two sensors are used for the measurement of the temperature and the humidity of the environment. The ZigBee modules is used for the transmission of the sensor data flow. There are two ZigBee modules in the simulation including data sending module and data receiving module. On the sending side, a ZigBee module which powered by the charging battery collects the data flow detected by the temperature and humidity sensors, and sends it out via the wireless network. On the receiving side, another ZigBee module receives the data flow via the wireless network. The server can get the data flow after the data processing, and the received data flow can be analyzed to supply the decision making support to the operator of the high speed railway.

The experiment is carried out on condition that the frequency and correlation are 8Hz and 1.25 m/s² respectively. Before the charging process, the voltage of the lithium battery is 2.4V. After the one hundred and fifty minutes' charging process, the lithium battery increases to 3.0V, shown as Fig.5(c) and the *supporting video 1*. What's more, on the receiving side, the data can show on the sever interface which means that on the sending side, ZigBee module can operate normally with the charged battery as shown in *supporting video 2*. And the temperature and humidity on the train are measured as 22 degree Celsius and 35%RH respectively, shown as Fig.5(d).The data will provide the railway operator with the decision-making support.

Fig.5 (a) Schematic diagram for railway vibration simulation platform. (b) Physical diagram for railway vibration simulation platform. (c) The battery voltage before charging process and the battery voltage after charging process. (d)The temperature and humidity data detected via sensors.

5.Conclusions

In summary, this paper proposes a self-powered TEVA which can effectively convert vibration energy into electricity. To ensure as much contact area as it can be attained, the Kapton nano structure and the aluminum nano structure are used for the contact surfaces. What's more, compared to previously reported designs in which the gap between two substrates are not well considered, this paper carries out several simulations based on the spring-mass model. According to the simulated result, the amplitude of the upper substrate reaches the highest value when the

vibration frequency is 9.5Hz and Fig.4(c) provides a reliable choice to the gap design of the TEVA. The experimental result shows that the peak voltage has positive linear correlation to the vibration frequency and the vibration acceleration. Due to the sensibility of the TEVA to the change of charges, the TEVA has a good performance when monitoring the acceleration. Therefore, it can be installed into the RSHM system for the fault diagnosis of the train key equipment.

To test the performance of the TEVA, a power supply circuit is designed for regulating the voltage output. Then the regulated voltage is used to charge the battery which supplies power to the ZigBee module. The output voltage of designed circuit for the TEVA is 3.3V which is high enough to charge the battery and provide enough and stable DC voltage for the following circuit. The ZigBee module is fully operational with the charged battery and the detected data can be sent out with the ZigBee technology, which can supply the decision making support to the operator of the high speed railway. These results will widen the spread of the RSHM system.

ACKNOWLEDGEMENT

This research are supported by the National Key Research and Development Program of China (No. 2016YFB1200203), National Natural Science Foundation of China (60706031 and 61574015), Beijing; National Science Foundation (4122058,4172051), Beijing Higher Education Young Elite Teacher Project (YETP0536), the State Key Laboratory of Rail Traffic Control and Safety (RCS2016K009), Beijing Jiaotong University and the “Talents Project” of Beijing Jiaotong University.

METHODS SUMMARY

RIE etching of the Kapton Nano Structure and characterization: To create the nanowire structures on the surface of the Kapton thin film (50 μ m), an induced coupled plasmon (ICP) reactive ion-etching technique was used. Specifically, Ar, O₂, and CF₄gases were introduced into the ICP chamber with the flow rate of 15.0,10.0, and 30.0 sccm, respectively. One power source of 400 W was used to generate a large density of plasma, and the other power of 100 W was used to accelerate the plasma ions. The Kapton thin film was etched for 5 min, and the length of the as-fabricated nanowire array ranged from 0.4 to 1.1 μ m. One power source of 400 W was used to generate a large density of plasma, and the other power of 100 W was used to accelerate the plasma ions. A Hitachi SU8010 field emission scanning electron microscope (SEM) was used to measure the size and height of NS on Kapton film.

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