第 17 卷　第 6 期
2009 年 6 月
光学 精密工程
Optics and Precision Engineering
Vol. 17　No. 6
Jun. 2009

文章编号　1004-924X(2009)06-1327-06

压电陶瓷轮胎发电机的设计

廖海洋，钟正青
（重庆大学 光电学院 新型微纳器件与系统技术国家重点学科实验室，重庆 400044）

摘要：为解决汽车轮胎压力无线监测系统（TPMS）电能自给问题，应用压电换能原理，提出将 PZT5 压电振子复合在轮胎内底面，把运行中的机械能转换为电能为无线发射模块供电的思想，设计了一种压电陶瓷轮胎发电机。建立了双层膜压电振子的有限元（FEA）模型，运用 ANSYS 11.0 对不同尺寸的振子进行静力和瞬态分析，得出设计振子尺寸的依据。针对单个振子发电量低的状况，提出采用阵列方式增大发电量的方案，设计了一种多振子电量耦合输出调节控制电路。选择振子尺寸为 40 mm×15 mm，实验得到单片压电振子在 15 Hz 固定形变的激励下，有效输出电流为 5 μA，峰值电压为 5 V 以上。当振子数量为 40 个以上时，轮胎发电输出的功率能满足 TPMS 休眠模式耗电 30 μW，发射耗电 35 mW，间歇时间 30 s 的需要。实验表明，压电阵列式轮胎发电机平均输出功率为 150～350 μW，瞬时输出功率可达到 50 mW。

关　键　词：轮胎发电机；计算机仿真；压电换能；有限元法
中图分类号：TM31　　**文献标识码**：A

Design of piezoelectric power generator in tire

LIAO Hai-yang, ZHONG Zheng-qing

(*National Key Laboratory of Fundamental Science of Micro/Nano Device and System Technology, Department of Optoelectronic Engineering, Chongqing University, Chongqing* 400044, *China*)

Abstract: A novel power generator in the tire which is applied in a wireless Tire Pressure Monitor System(TPMS) was designed. The piezoelectric convertor constructed by bender arrays was merged to the inner surface of a tire to transform the mechanical deformation into the electric power and supply to the sensors of TPMS. A Finite Element Model(FEM) for the convertor was established based on the second piezoelectric function and the piezoelectric convertor with different sizes was analyzed by ANSYS 11.0 in a transient method. Then, a target of 6 cm^2 was selected to observe its characteristics, and the effective current is 5 μA. As the wireless sending component needs 10 mA every 30 s, an array with 40 piezoelectric convertors was used in the generator and a power conditioning circuit with a multiple path charge coupling module was also designed. Experiments show that when the frequency of tire rotation is 15 Hz, the average power through the conditioning circuit is 150—350 μW and the instantaneous power can reach 50 mW, which proves that the power generator can work efficiently.

Key words: power generator in tire; computer simulation; piezoelectric convertor; Finite Element Method(FEM)

Received date: 2009-01-20; **Revised date**: 2009-04-30.

Foundation item: Supported by the National Hi-Tech Research and Development Program of China (863 Program) (Grant No. 2005AA404280)

1 Introduction

The vast reduction in size and power consumption of COMS circuitry has led to a large research effort based around the vision of ubiquitous networks of wireless sensor and communication nodes. With the increase in number of devices and the decrease in size, the replacement of depleted batteries becomes impractical, so the wireless nodes needs to be self-powered[1]. In this case we are dealing with the micro power generator for wireless tire pressure monitoring system (TPMS).

Mechanical vibrations have received attention from various researchers as a potential source of power for sensors and wireless electronics in a wide variety of applications. Generators based on electromagnetic, electrostatic, and piezoelectric conversion have been suggested in the literature[2].

In the paper a design of power generator in tire based on piezoelectric conversion is put forward. Because of the highly energy density and small size, the piezoelectric convertor can be placed on the inner surface of tire. Convertors will transform the mechanical deformation into electric power to support wireless sensor network while the tire is rolling.

2 Generator configuration

A target size of 1 cm×4 cm has been selected, which is based on the size of typical wireless sensor network. The power of signal sending component ranges from several μW to hundred. 8 parallel groups of convertors are attached onto the inner surface with an equal interval along the circumference of tire and each group includes 4 benders. The wireless sending component is placed onto wheel hub, as shown in Fig. 1 and Fig. 2.

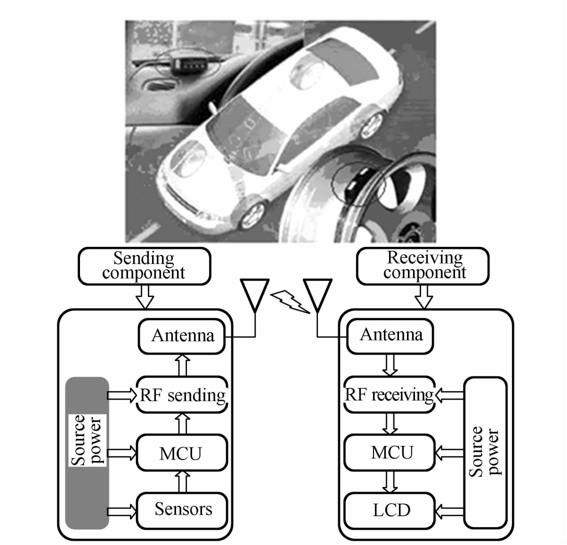


Fig. 1 Wireless TPMS in car

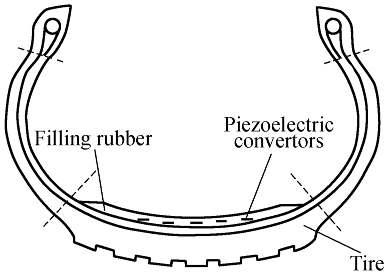


Fig. 2 Piezoelectric convertors in tire

Because of the gravity, the surface of tires contacting with road deforms to flat during the running of cars. By the mean time, those piezoelectric convertors are bended by tires continuously. So they can convert the mechanical energy into electrical power. And regulated voltage is sent to wireless sensor networks after a power conditioning circuit. The generator can work as batteries for TPMS.

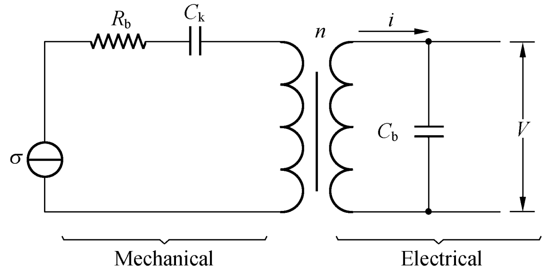
3 Electro-mechanical model

By analyzing the structure of piezoelectric material we came to a conclusion that the equation of state can be described by the second piezoelectric function[3], which is written in reduced-matrix form as:

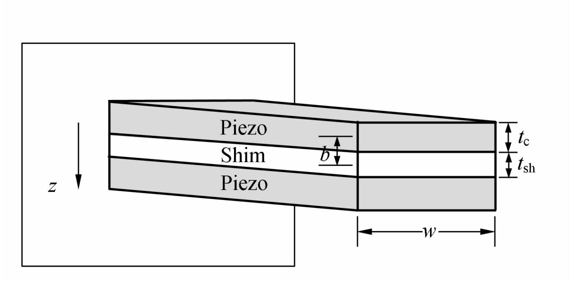
$$\left.\begin{aligned}\boldsymbol{T}&=\boldsymbol{C}^{E}\boldsymbol{S}-\boldsymbol{e}\boldsymbol{E}\\ \boldsymbol{D}&=\boldsymbol{e}\boldsymbol{S}+\boldsymbol{\varepsilon}^{s}\boldsymbol{E}\end{aligned}\right\}\text{or}\begin{bmatrix}\boldsymbol{T}\\ \boldsymbol{D}\end{bmatrix}=\begin{bmatrix}\boldsymbol{C}^{E} & -\boldsymbol{e}'\\ \boldsymbol{e} & \boldsymbol{\varepsilon}^{s}\end{bmatrix}\begin{bmatrix}\boldsymbol{S}\\ \boldsymbol{E}\end{bmatrix}, \quad (1)$$

Where $\boldsymbol{S}$ is the six-dimensional train vector, $\boldsymbol{T}$ is the vector of stresses, $\boldsymbol{D}$ is the three-dimensional electric displacement vector, $\boldsymbol{E}$ is the electric field vector, $\boldsymbol{C}^E$ is the six by six compliance matrix evaluated at constant electric field, $\boldsymbol{e}$ is the three by six matrix of piezoelectric train coefficients.

So a two-layer bending element as a power generator is assumed and electrodes are placed on the surfaces perpendicular to the z axis. Most vibrations exist only along the z axis. A circuit of the generator is shown in Fig. 3.



(a) Electro-mechanical model of piezoelectric convertor



(b) Layer structure of a bender

Fig. 3 Schematic of piezoelectric convertor and bender structure

Those assumptions are based on the model of Roundy[1], where the equivalent resistor, R_b, represents mechanical damping, the equivalent capacitor, C_k, represents the mechanical stiffness. σ is equivalent tress generator that represents the stress developed as a result of the input deformations, n represents the equivalent turn ratio of the transformer and C_b is the capacity of the piezoelectric convertor. Thus the used stress variable is σ not T, and the stress-strain relationship is $S = s\sigma$ (or $\sigma = cS$).

For purely electrical circuits, the system equations are then determined by Kirchhoff's voltage law (KVL) and current law (KVL). Taking the sum of 'voltages' around the mechanical side of the circuit yields the expression, as shown in equation (2).

$$\sigma_{in} = R_b\dot{S} + S/C_k + nV\ . \tag{2}$$

And the other parameters are given by the following equations.

$$i = C_b\dot{V}\ , \tag{3}$$

$$\sigma_{in} = \frac{F_{in}}{b}\ . \tag{4}$$

The input stress σ is decided by the thick ness of bender b and the deformation along the z axis. Substituting them into equation (2), we can calculate the relationship between T and output voltage V.

$$T = \frac{-d_{31}c_p}{2t_c}V\ . \tag{5}$$

Then $n = -d_{31}c_p/2t_c$, where C_p is the elastic constant for the piezoelectric material. Finally the output voltage has the following form.

$$V = \frac{2t_c(F_{in} - b_c k^2\dot{S} - c_p kS)}{d_{31}c_p}\ . \tag{6}$$

4 Finite element model of transformer and simulation by ANSYS 11.0

Using piecewise-linear function to represents the displacement of every divided nodal along the convertor[4]. Supposing displacement of element x_i has the following expression:

$$u(x,t) = (1,x)\begin{bmatrix}\alpha_0(t)\\ \alpha_1(t)\end{bmatrix} =$$

$$\left(\frac{x_i - x}{x_i - x_{i-1}}, \frac{x - x_{i-1}}{x_i - x_{i-1}}\right)\begin{bmatrix}u_{i-1}(t)\\ u_i(t)\end{bmatrix}$$

$$\text{where } (x_{i-1} \leqslant x \leqslant x_i)\ . \tag{7}$$

The equation of variation can be written as equation (7) using expression of gross stiffness and electro-mechanical coupling vector.

$$\begin{cases} \boldsymbol{KU}(\boldsymbol{t})+\boldsymbol{M}\ddot{\boldsymbol{U}}(\boldsymbol{t})=\boldsymbol{P}V \\ \boldsymbol{P}^{\mathrm{T}}\boldsymbol{U}(\boldsymbol{t})+C_0V=Qt \end{cases}, \tag{8}$$

And nodal solution

$$\begin{cases} \boldsymbol{K}_{\mathrm{aa}}\boldsymbol{U}_{\mathrm{a}}+\boldsymbol{M}_{\mathrm{aa}}\ddot{\boldsymbol{U}}_{\mathrm{a}}=\boldsymbol{P}_{\mathrm{a}}V+\boldsymbol{F}_{\mathrm{a}} \\ \boldsymbol{K}_{\mathrm{ab}}{}'\boldsymbol{U}_{\mathrm{a}}+\boldsymbol{M}_{\mathrm{ab}}{}'\ddot{\boldsymbol{U}}_{\mathrm{a}}=\boldsymbol{P}_{\mathrm{b}}V+\boldsymbol{F}_{\mathrm{b}} \end{cases}, \tag{9}$$

Where $\boldsymbol{M}$ is gross mass matrix, $\boldsymbol{K}$ is gross stiffness matrix, $\boldsymbol{P}$ is gross electro-mechanical coupling vector. By knowing nodal displacement $\boldsymbol{U}(\boldsymbol{t})$, we can calculate force $\boldsymbol{F}_{\mathrm{B}}$ and quantity of electricity $\boldsymbol{Q}$ can be calculated.

ANSYS 11.0 is a common computer simulation software. Piezoelectric analysis belongs to coupling filed analysis[4]. Calculations are based on direct coupling field. Element type of PZT-5 is solid 226. Fig. 4 shows a single periodic analysis.

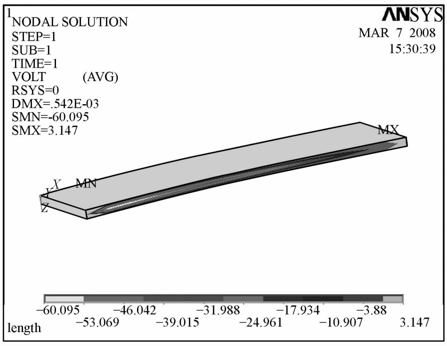


Fig. 4 ANSYS model of one bender

The process of analysis is as follows:

(1) Creat an ANSYS model by following parameters. Both piezoelectric layers are 139 μm, and elastic metal in the middle is 102 μm shown in Fig. 3. Input elastic matrix permittivity matrix and piezoelectric matrix.

(2) Mash it by a smart size element.

(3) Analyze it by a transient method. It can be divided into five time steps to describe the procedure of one cycle. On different time point can be given by different loads.

(4) Set up restrains on the convertors, force load, time steps, and the start solve.

(5) After processing, calculate a voltage-time curve and come out the effective voltage of the whole procedure, as shown in Fig. 5. Effective voltage of this curve is given by the equation (10).

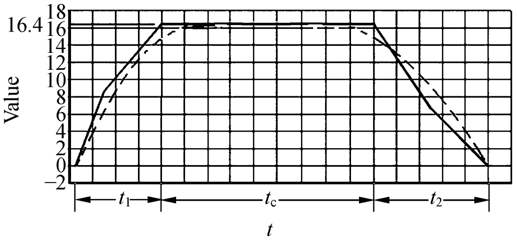
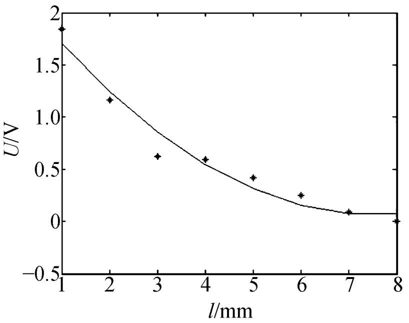
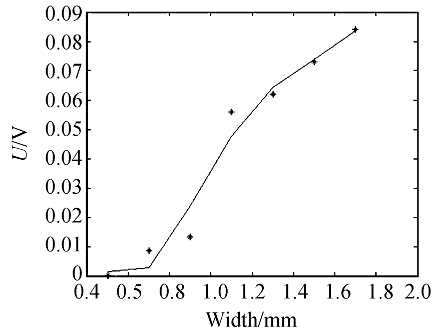


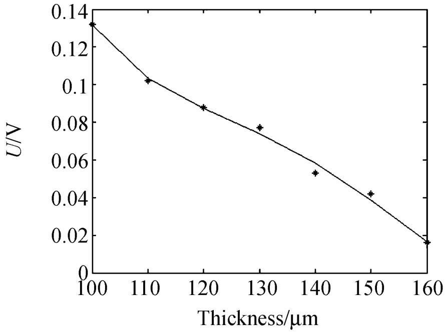
Fig. 5 Voltage in one procedure



(a) Voltage-length curve



(b) Voltage-width curve



(c) Voltage-thickness curve

Fig. 6 Curves of voltage-length, voltage-width and voltage-thickness

$$u_a = \sqrt{\frac{\int_0^{t_1} u_t^2 dt + \int_{t_1}^{t_c} u_t^2 dt + \int_{t_c}^{t_2} u_t^2 dt}{t_2 - 0}} \approx 0.133\ \text{V}. \tag{10}$$

By repeating this process at different sizes of the convertor, the relationship between voltage and dimension can be solved. Curves have been fitted out by least square method, as shown in Fig. 6. A proper size can be chosen to fit the demand before the engineering design to reduce the cost.

5 Power conditioning circuit

A power conditioning circuit can be used to regulate the power and supply energy to low-power electronic device, sensors and remote circuit with high instantaneous power consumption in the environment of mechanical deformation. The circuit commonly seen in literatures[1-2] has a limitation on output power (usually between several μW to tens), but sometimes the transmitting component need several mW. So a structure of convertor arrays has been brought in. The assistant circuit is to supply the hysteresis comparator, electrical switch and fulfill the demand of power consume, as shown in Fig. 7[6]. After the experimental test the time-averaged output power of this circuit is 250~950 μW and instaneous power is 680 mW. The consumed power is only below 40 μW. All the output power of convertor has been calculated by an average rotation frequency of 30 Hz.

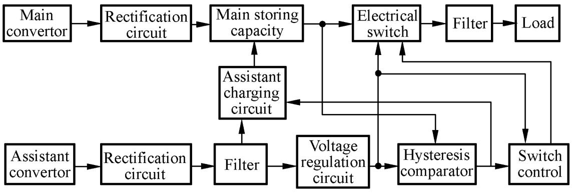


Fig. 7 Power conditioning circuit for piezoelectric transformer

6 Conclusions

As wireless sensor systems are decreasing in size and power consumption, an effective micro power supply is needed. The model for a generator based on piezoelectric convertor has been developed. The results of type selection and power conditioning circuit will be helpful in further application.

References:

[1] ROUNDY S, WRIGHT P K. A piezoelectric vibration based generator for wireless electronics [J]. *Institute of Physics Publishing*, 2004, 13: 1131-1142.

[2] LORETO M, FRANCESC M. Appropriate charge control of the storage capacitor in a piezoelectric energy harvesting device for discontinuous load operation [J]. *Sensors and Actuators*, 2006, 132: 302-310.

[3] QU Y F. *Physical Performance of Functional Ceramics* [M]. Beijing: Higher Education Press. (in Chinese)

[4] LOU L F, YANG Y T. Applications of ANSYS on PZT piezoelectric fiber sensor system′s simulation [J]. *Mechanical Science and Technology*, 2005, 24: 875-878. (in Chinese)

[5] ZHAO M L, HUANG Q, ZHANG W. Investigation on design method of single chamber piezoelectric pump with cantilever valve [J]. *Opt. Precision Eng.*, 2006, 14: 607-611. (in Chinese)

[6] LIAO H Y. A power conditioning circuit for micro piezoelectric power generator by multi-convertor structure [P]. CHINA: 200710092465.4, 7-20-207. (in Chinese)

[7] ZENG P, WEN J M, CHENG G M. Research on novel inertial piezoelectric actuator [J]. *Opt. Precision Eng.*, 2006, 14: 623-627. (in Chinese)

Authors' biographies:

LIAO Hai-yang (1956－), male, professor of the National Key Laboratory of Fundamental Science of Micro/Nano Device and System Technology, Chongqing University, his research interests are MEMS technology, metering and testing technology, intelligent optoelectronic instrument *etc*.. **E-mail**: hyliao@cqu.edu.cn

ZHONG Zheng-qing (1983－), male, M.S. of the College of Opto-electronic Engineering, Chongqing University, his research interests are MEMS technology *etc*.. **E-mail**: zzq6174@yahoo.com.cn

---

●下期预告

非合作航天器相对位姿测量方法

徐文福，刘　宇，梁　斌，李　成，强文义
(哈尔滨工业大学 空间智能系统研究所，黑龙江 哈尔滨 150001)

为了解决在轨维护和轨道垃圾清除中非合作目标的识别问题，提出了基于立体视觉的位姿(位置和姿态)测量方法。采用中值滤波器对原始图像进行平滑，去除星空背景干扰和其它噪声；将 Canny 边沿检测器用于对平滑后的图像进行检测，得到包含边沿信息的二值图像。然后，对该二值图像进行 Hough 变换，提取待识别对象的直线特征，并计算直线间的交点。最后，对所提取的左、右相机图像的点特征进行 3D 重构，得到各点在世界坐标系中的坐标，并据此建立目标坐标系，进而求出其相对于世界坐标系的位置和姿态。仿真结果表明，对于较远距离(>2.5 m)，位置测量精度优于 40 mm，而近距离内(<2.0 m)优于 10 mm，相对姿态精度优于 2°。基本满足对非合作目标进行跟踪、接近、绕飞等位姿测量要求。