2015

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A CYLINDRICAL TRIBOELECTRIC ENERGY HARVESTER FOR CAPSULE ENDOSCOPES

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***Abstract*—Capsule endoscopy is a new technology that has the potential to replace conventional endoscopy in the near future due to its non-invasive nature. A major limitation for their functionality is the limited battery life. We have investigated a triboelectric energy harvester inside a capsule endoscope that can generate power from natural contractions of gastrointestinal (GI) tract. The periodic contacts and separations of two triboelectric materials inside the capsule endoscope create an alternating current that can be used to charge the capsule endoscope battery, which is used for imaging the GI tract. This study presents an analytical closed form solution for the output power of a cylindrical triboelectric energy harvester. Energy harvester sizes have been optimized to maximize the output power.**

I. INTRODUCTION

Energy harvesting, i.e., generating electricity from human passive motions, have been studied using piezoelectric [1], electromagnetic [2] and triboelectric effects [3]–[6]. Although the power produced is in the milliwatts range, it is useful for operation of low-power biomedical sensors or energy storage in a capacitor. Among different mechanisms for energy harvesting, triboelectric effect has been proven to be as the most recent effective method for converting low frequency vibrations with the power density of 313 W/m^2. Triboelectric energy harvester consists of a top layer made of a polymer/conductor and a bottom layer made of a conductor. Upon periodic contact and separation of polymer/conductor surface, triboelectric charges are produced that induce an electrostatic charge on the conductor, which is attached to the polymer surface. Once two conductors are connected through a wire, alternating current is produced that can be expressed as $I = dQ/dt$. The current is generated due to both the change in the potential from triboelectric charges and the change in the capacitance once two plates are separated from each other [7].

The goal of this research is to investigate the triboelectric energy harvesting as an energy support system for wireless capsule endoscopes. Capsule endoscope is a new non-invasive technology that has the potential to replace conventional endoscope to diagnose GI tract diseases. It consists of a pill-shaped device equipped with a camera and LEDs, a coin battery and a data transmission module. Due to the stringent size constraint (i.e., usually less than 1 inch), conventional capsule endoscopes usually have a life spanning from 20 minutes to a few hours. Given lots of uncertainty during the operation, the device may need to stay inside the GI tract for a longer period of time [8], [9]. It is thus highly desired to seek other alternative such as self-harvested power sources that can support such miniature-sized devices. To better accommodate the geometric form factor of the capsule endoscope, as shown in Fig. 1c, we propose a novel cylindrical triboelectric energy harvester (CTE). The energy harvester consists of an outer cylinder shell made of Aluminum and an elastomer, and an inner cylinder made of two layers of Polydimethylsiloxane (PDMS) and Al. Polydimethylsiloxane belongs to a group of polymeric organosilicon compounds. It is widely used in contact lenses and medical devices. Our CTE can be embedded into the conventional capsule endoscopes, and can take advantage of the continuous contraction of the GI tract to squeeze and release the CTE and thus generate the electrical energy that can be used for supporting the endoscopes. The reported hoop stress of GI tract is about 62 KPa during fasting and about 121 KPa after meals [10], which we anticipate to be sufficient to squeeze the CTE.

The key for maximizing the power generation in triboelectric generators is to increase the surface area with micropatterns, amongst which micro pyramids were shown to be the most effective solutions.

II. ANALYTICAL STUDY OF A CTE

A 3-D model for the CTE is shown in Fig. 1a and b. The inner green cylinder contains a capsule endoscope and its components. The red shell refers to a PDMS shell, and the blue shells refer to Aluminum and elastomer shells. The two yellow hemispheres are lids of the whole device. Fig. 1a shows the original state of the generator, and Fig. 1b shows the deformation of the harvester when the GI tract squeezes.

Fig. 2 shows the working steps of the proposed generator. In the original state of the device (Fig. 2a), there is no charge transferred. When pressure is applied on the outer shell, the PDMS and Al film will contact each other, and will have relative sliding at the nano-texture contact surface of two shells, which generates triboelectric charges on the contact surfaces. Due to the different abilities to gain and loose electrons of PDMS and Al, the electrons will be injected from Al to the PDMS surface, therefore leaving the positive charges on the surface of Al (Fig. 2b). The insulating property of PDMS allows the charges to hold for hours. Once the pressure is released, the outer shell will rebound to its original state due to the flexibility of the elastomer film. The potential

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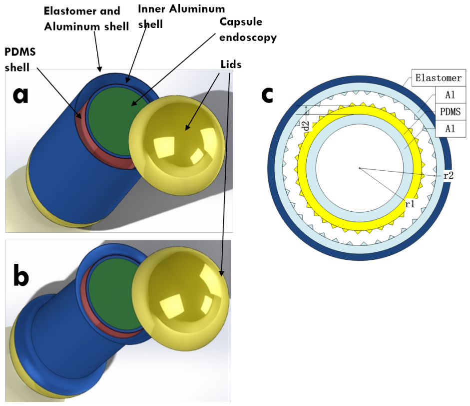

Fig. 1: Cylindrical triboelectric energy harvester **a.** 3-D model in its original state **b.** 3-D model after GI tract contraction **c.** cross section view

difference will drive the flow of positive charges from Al to the inner electrode (inner Al) which shows an external current (Fig. 2c). When the potential difference is offset by the transferred charges, the current vanishes (Fig. 2d). When the two shells are fully in contact again, as a result of the GI tract contraction, the electric potential difference approaches zero from a large value, because at the contact the charges are confined only to the surface and are almost on the same plane. This change in the potential difference creates an instantaneous current in the reverse direction (Fig. 2e). Finally, when the current vanishes again, the device will return to its equilibrium state. The first step towards predicting the output power is to find the relationship between mechanical deformation and the potential difference between two electrodes of the harvester.

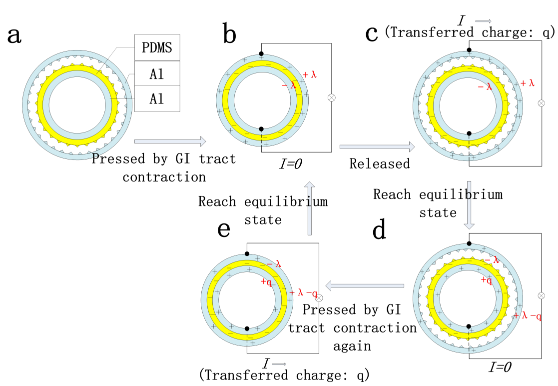

Fig. 2: Schematic of working steps of the energy harvester

A. *Potential Difference and Radial Deformation*

The potential difference between the two radial electrodes of the energy harvester is caused by two different charges: triboelectric and transferred charges. The triboelectric length (unit) charge density is called λ, which indicate the charges per unit length (L) of the cylinder (the charges on the periphery of a circle at each cross section of the cylinder). The transferred charges between the two electrodes are defined as $Q = q \times L$. The first step is to calculate each value of electric field, E.

$$E_\lambda = \frac{\lambda}{2\pi\varepsilon_0 r} \tag{1}$$

$$E_Q = \frac{Q}{2\pi\varepsilon_0 r L} \tag{2}$$

Eqs. (1) and (2) are the electric field of the triboelectric charges (E_λ) and the transferred charges (E_Q), where ϵ_0 is the permittivity of air.

The electric field in the air is

$$E_{air} = \frac{\lambda}{2\pi\varepsilon_0 r} - \frac{Q}{2\pi\varepsilon_0 r L} \tag{3}$$

The electric field inside the PDMS can be expressed as

$$E_{PDMS} = -\frac{Q}{2\pi\varepsilon_0\varepsilon_{r2} r L} \tag{4}$$

Thus the potential difference in the air gap is obtained as follows:

$$V_{r2} - V_{r1} = -\int_{r1}^{r2} E_{air} dr = \left(\frac{\lambda}{2\pi\varepsilon_0} - \frac{Q}{2\pi\varepsilon_0 L}\right)\ln\left(\frac{r2}{r1}\right) \tag{5}$$

The potential difference in the PDMS is

$$V_{r1} - V_{r1-d2} = -\frac{Q}{2\pi\varepsilon_0\varepsilon_{r2}L}\ln\left(\frac{r1}{r1-d2}\right) \tag{6}$$

Therefore, the total potential difference between the two electrodes is

$$\begin{aligned} V_{r2} - V_{r1-d2} = &\left(\frac{\lambda}{2\pi\varepsilon_0} - \frac{Q}{2\pi\varepsilon_0 L}\right)\ln\left(\frac{r2}{r1}\right) \\ &- \frac{Q}{2\pi\varepsilon_0\varepsilon_{r2}L}\ln\left(\frac{r1}{r1-d2}\right) \end{aligned} \tag{7}$$

Because $r2 = r1 + x$, where x is the air gap between the Al and the PDMS, the potential difference can be expressed as

$$\begin{aligned} V = &\left(\frac{\lambda}{2\pi\varepsilon_0} - \frac{Q}{2\pi\varepsilon_0 L}\right)\ln\left(\frac{r1+x}{r1}\right) \\ &- \frac{Q}{2\pi\varepsilon_0\varepsilon_{r2}L}\ln\left(\frac{r1}{r1-d2}\right) \end{aligned} \tag{8}$$

B. *Instantaneous Current, Voltage, and Power*

In practice, CTE is connected to an arbitrary resistor R, so the voltage across resistor is

$$V = IR = R\frac{dQ}{dt} \tag{9}$$

Equating the Eqs. (8) and (9), we obtain

$$R\frac{dQ}{dt} = (\frac{\lambda}{2\pi\varepsilon_0} - \frac{Q}{2\pi\varepsilon_0 L})\ln(\frac{r1+x}{r1}) - \frac{Q}{2\pi\varepsilon_0\varepsilon_{r2}L}\ln(\frac{r1}{r1-d2}) \tag{10}$$

Eq. (10) is a first order variable coefficient differential equation, which considers the case at $t = 0$, the two shells are close to each other, and the initial condition is $Q(t = 0) = 0$. Eq. (10) can be solved as

$$Q(t) = \lambda L - \lambda L e^{A(t)} + e^{A(t)}\int_0^t \frac{\lambda\ln(\frac{r1-d2}{r1})}{2\pi\varepsilon_0\varepsilon_{r2}R}e^{-A(\tau)}d\tau \tag{11}$$

where

$$A(t) = \frac{\int_0^t \left[\ln(\frac{r1-d2}{r1}) + \varepsilon_{r2}\ln(\frac{r1}{r1+x(t)})\right]dt}{2\pi\varepsilon_0\varepsilon_{r2}RL} \tag{12}$$

Instantaneous current is $I(t) = dQ/dt$, and can be found by differentiating Eq. (11) in respect to t

$$I(t) = \frac{\lambda C1}{2\pi\varepsilon_0\varepsilon_{r2}R} - \lambda L\frac{C1+a(t)}{2\pi\varepsilon_0\varepsilon_{r2}RL}e^{A(t)} + e^{A(t)}\frac{C1+a(t)}{2\pi\varepsilon_0\varepsilon_{r2}RL}\int_0^t \frac{\lambda C1}{2\pi\varepsilon_0\varepsilon_{r2}R}e^{-A(\tau)}d\tau \tag{13}$$

where

$$C1 = \ln(\frac{r1-d2}{r1}) \tag{14}$$

$$a(t) = \varepsilon_{r2}\ln(\frac{r1}{r1+x(t)}) \tag{15}$$

The instantaneous voltage is also found as

$$V(t) = RI(t) = \frac{\lambda C1}{2\pi\varepsilon_0\varepsilon_{r2}} - \lambda L\frac{C1+a(t)}{2\pi\varepsilon_0\varepsilon_{r2}L}e^{A(t)} + e^{A(t)}\frac{C1+a(t)}{2\pi\varepsilon_0\varepsilon_{r2}L}\int_0^t \frac{\lambda C1}{2\pi\varepsilon_0\varepsilon_{r2}R}e^{-A(\tau)}d\tau \tag{16}$$

One should note that when t exceeds x_{max}/v, the analytical equations for $Q(t)$ need to be recalculated by setting $x = x_{max}$ in Eq. (10) and applying a boundary condition as $Q(t = x_{max}/v) = Q_0$, and Q_0 can be calculated by assigning t equals to x_{max}/v into Eq. (11).

Finally, the output power is obtained as $P = V(t)I(t)$.

III. Simulation Results

The output power of the harvester is examined under two assumptions of constant and variable velocities as expressed in the following two equations, respectively. Using the second motion mode (variable velocity), we study the effects of different size parameters of the energy harvester on its output [11].

$$\begin{cases} x = vt(t < \frac{x_{max}}{v}) \\ x = x_{max}(t \geq \frac{x_{max}}{v}) \end{cases} \tag{17}$$

$$\begin{cases} x = x_{max}\left[\frac{1}{2} - \frac{1}{2}cos(\frac{\pi v}{x_{max}}t)\right](t < \frac{x_{max}}{v}) \\ x = x_{max}(t \geq \frac{x_{max}}{v}) \end{cases} \tag{18}$$

The velocity, v in Eq. (18) is the average velocity that can be expressed in terms of contraction frequency, f as $v = \Phi f$, where Φ is the diameter of the GI tract, which is usually set as 25 mm [12].

The variation in the maximum output power versus changes in initial gap, length charge density, capsule length, radius of inner shell, PDMS thickness, and frequency are shown in Figs. 3 a-f. As it can be deduced, when the initial gap is near 2mm, the output power can reach its maximum value. Larger length, higher frequency, larger linear charge density contribute to larger output power. In contrast, smaller PDMS thickness, and smaller inner radius lead to larger output power. However, the length and the inner radius are constrained by capsule size limitations and can't be changed.

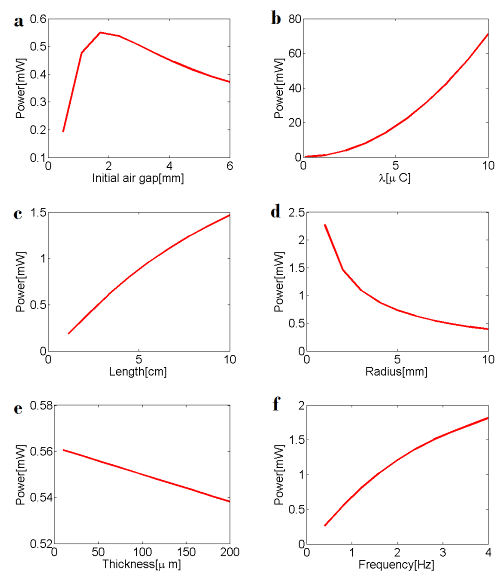

Fig. 3: Maximum output power of the proposed energy harvester versus **a.** initial air gap, **b.** length charge density, **c.** capsule length, **d.** inner radius, **e.** PDMS thickness, and **f.** deformation frequency

The parameters that can be used to optimize the design are the PDMS thickness and length charge density. The PDMS thickness is chosen to be 100 microns, although smaller thickness can yield larger power. The length charge density can be increased by increasing the surface area using micro patterns on the PDMS and Al surfaces or using two triboelectric materials that are located farther from each other in the triboelectric table series. The frequency of CTE depends on the frequency of contraction inside the GI tract and there is no unique value for it in the literature. Woo *et al.* [13] measured the small intestine contractile motion using a telemetry capsule, and the periodic pressure of the small intestine is shown as Fig. 4. The frequency of contraction is 0.33 Hz or 20 CPM. However, we estimate after drinking and due to speeding of the capsule endoscope using external magnetic navigation systems, the frequency of peristalsis is shown to be 40 CPM. Assuming the GI tract has a variable velocity with the motion described in Eq. (18), and using the frequency of 40 CPM, the output power of the energy harvester is simulated versus resistance in the connected circuit as shown in Fig. 5b. The output power for the constant velocity case of the GI tract is shown in Fig. 5a. The optimized parameter values used are listed in Table I.

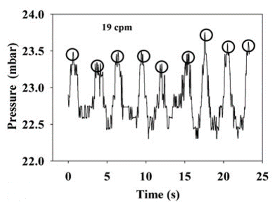

Fig. 4: Periodic pressure of the small intestine [13]

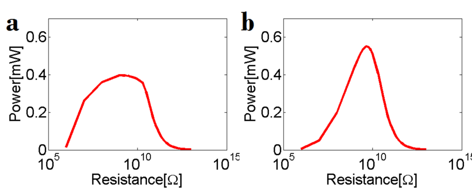

Fig. 5: The output power versus resistance for **a.** constant velocity motion and **b.** variable velocity motion

When the resistance reaches $1G\Omega$ and $5G\Omega$, the output power reaches its maximum values of 0.4 and 0.54 mW for the constant velocity and variable velocity motion, respectively.

TABLE I: Optimized parameters used for the simulations

Parameters	Value
Thickness of PDMS	$d2 = 100\ \mu m$
Frequency	$f = 0.67\ Hz$
Air dielectric constant	$\varepsilon_0 = 8.85 \times 10^{-12}\ F \cdot m^{-1}$
Relative dielectric constant of PDMS	$\varepsilon_{r2} = 3.4$
Length of the cylinder	$L = 30\ mm$
Maximum gap between PDMS and Al	$x_{max} = 2\ mm$
Inner radius	$r1 = 7\ mm$
Unit charge density	$\lambda = 0.880 \times 10^{-6}\ C \cdot m^{-1}$

IV. Conclusion

The closed form expression for estimating the output power for a cylindrical triboelectric energy harvester inside a wireless capsule endoscope was explored and established. The effects of capsule size and frequency, length charge density, and frequency of GI tract peristalsis on maximum output power were investigated. It is found that the maximum output power of the proposed harvester can reach to a level of approximately half of a milliwatt, in its current setting. The output power also depends on the resistance of the circuit that it connects to, according to our study, which can result in the maximum output power when $R = 1G\Omega$ for constant contraction velocity mode and $R = 5G\Omega$ for variable contraction velocity mode. In addition to the output power, we also demonstrated the instantaneous charges, current and voltage. Capsule endoscope was only one example that we have examined for the cylindrical triboelectric energy harvester was employed. The analytical study presented here can be applied to estimate the scavenged power from any natural mechanical contraction that occurs in a cylindrical configuration. Future applications of the CTE can expand the emerging low power wearable biomedical sensors for an improved health care system. For now, our results are mainly on analytical modeling. The future plan is conduct experiments to verify simulation results.

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