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Piezoelectric energy harvesting from heartbeat vibrations for leadless pacemakers

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Abstract. This paper studies energy harvesting from heartbeat vibrations using fan-folded piezoelectric beams. The generated energy from the heartbeat can be used to power a leadless pacemaker. In order to utilize the available 3 dimensional space to the energy harvester, we chose the fan-folded design. The proposed device consists of several piezoelectric beams stacked on top of each other. The size for this energy harvester is 2 cm by 0.5 cm by 1 cm, which makes the natural frequency very high. High natural frequency is one major concern about the micro-scaled energy harvesters. By utilizing the fan-folded geometry and adding tip mass and link mass to the configuration, this natural frequency is reduced to the desired range. This fan-folded design makes it possible to generate more than 10 μW of power. The proposed device does not incorporate magnets and is thus Magnetic resonance imaging (MRI) compatible. Although our device is a linear energy harvester, it is shown that the device is relatively insensitive to the heartrate. The natural frequencies and the mode shapes of the device are calculated. An analytical solution is presented and the method is verified by experimental investigation. We use a closed loop shaker controller and a shaker to simulate the heartbeat vibrations. The developed analytical model is verified through comparison of theoretical and experimental tip displacement and acceleration frequency response functions.

1. Introduction
Unlike traditional pacemakers, leadless pacemakers do not have leads and do not need an open surgery for implantation. The required power for a pacemaker is about 1 μW [1]. The main obstacle for the development of leadless pacemakers is the power issue, as its battery takes about 60% of the size of a conventional pacemaker. The size of the conventional pacemaker batteries is too large for leadless pacemakers. The battery size issue hindered the development of leadless pacemakers for 20 years. Recently novel batteries have been developed that make leadless pacemakers realizable [2]. Still, the battery life is the same as traditional pacemakers and it lasts 6 to 7 years [2]. Extraction of leadless pacemakers is very difficult so when the battery is depleted, a new pacemaker has to be implanted. It is shown that our proposed device generates an order of magnitude more power than the nominal power needed for a leadless pacemaker. The small size of the energy harvester and sufficient output

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power of the device are the advantages of this new design. The size of the device is 2cm × 0.5 cm × 1cm (1 cc in volume).

Several studies have been done on energy harvesting from heartbeat and fan-folded structure. None of the groups looked into energy harvesting for leadless pacemaker using fan-folded structure. Karami uses linear and non-linear design for pacemaker energy harvesting [3]. Khattak studies the interesting behaviour of a fan-folded structure [4]. He finds that structures with even beams have repeated resonances and structure with odd beams have double roots coinciding with a cantilevered beam. In another research, Reissman studies the coupling effect of vibration fan-folded energy harvesting structures [5]. In this research, a fan-folded structure is studied. The free vibration modes for a five beam structure are found and it is shown that the generated power of the structure is sufficient to power a pacemaker.

2. Device configuration

The device consists of several horizontal bimorph beams and vertical rigid beams. Each horizontal beam is a bimorph piezoelectric beam, with one brass layer as the substrate and two piezoelectric layers attached on each side. The bimorph beams are connected to each other by rigid links made from platinum. Platinum is chosen for the links due to its high density. One end of the structure is clamped as the other end is free to move (Figure 1 and Figure 2). High natural frequency is one major problem in small energy harvesters. In order to generate sufficient power for a pacemaker, the first natural frequency of the energy harvester should be less than 50 Hz. The fan-fold geometry is a very effective design to reduce the natural frequency. We also utilize the tip mass and the link masses to reduce the natural frequency of our device to 22 Hz.

3. Modelling and solving the governing equations

The device consists of several uniform composite beams and each beam is modeled with the Euler-Bernoulli beam theory. The structure vibrates due to base excitation. Each beam can bend and deflect which changes the start position of the next beam. The deflection of the beam \( w_i \) is a function of the length \( x \) and time \( t \). The index \( i \) is the beam number (from 1 to \( n \)). The coupled mechanical equation of a beam with tip mass is [6]:

\[
\rho A \frac{\partial^2 w_{rel}}{\partial t^2} + YI \frac{\partial^4 w_{rel}}{\partial x^4} = -\alpha \left[ \frac{d\delta(x)}{dx} - \frac{d\delta(x-L)}{dx} \right] v(t) - \rho A + m_i \delta(x - x^*, i - k) + M_i \delta(x - x_{end}, i - n) \frac{d^2 w_p}{dt^2} \tag{1}
\]

Where \( \rho A \) is the total mass per unit length of the beam. \( w_{rel}(x, t) \) is the deflection along the z-axis, \( YI \) is the equivalent bending stiffness of the composite beam. \( m_i \) is the link mass and \( x^* \) is 0 (if \( i \) is an
odd number) or length of the beam, \(L\), (if \(i\) is an even number). Index \(k\) is from 2 to \(n\). \(M_t\) is the tip mass, \(\delta(x)\) is the Dirac delta function and \(\alpha\) is the coupling term and for parallel connection. To find the vibration mode shapes, we solve the undamped, uncoupled equation. The solution for the free vibration can be shown as a linear combination of all natural motions of the beam [7] (Section 11):

\[
w_i(x,t) = \sum_{j=1}^{\infty} \phi_{ij}(x)T_j(t)
\]

(2)

Where, \(\phi_{ij}\) is the \(i^{th}\) mode shape of the \(j^{th}\) beam, and \(T_j\) is the time dependent function. By using the above equations and considering boundary and continuity conditions, the mode shapes and natural frequencies of a fan-folded structure are derived. In the configuration that we have, the beams are connected electrically in parallel. Since the deflection of the beams is opposite of each other in some frequencies of a fan-folded structure are derived.

\[
\sum_{j=1}^{\infty} T(t)j \phi_{ij} + \rho A \sum_{j=1}^{\infty} T_j(t) \phi_{ij} = -\alpha P_t \left[ \frac{d\delta(x)}{dx} - \frac{d\delta(x - L)}{dx} \right] v(t)
\]

(3)

\[- \left[ A + m_i \delta(x - x_i, i - k) + M_t \delta(x - x_{\text{end}}, i - n) \right] \dot{w}_b
\]

Where \(P_t\) is the switch for the \(i^{th}\) member and it is either 1 or -1. The sign of the switches for each mode is decided based on \(P_t = \text{Sign}(\phi_j'(0) - \phi_j(0))\). Using equation (3) and Kirchhoff laws for parallel connection we find the expression for the multi-mode power frequency response function. For more details on the mathematical modeling please refer to [9].

\[
p(\omega) = \frac{1}{2R} \left( \frac{\sum_{j=1}^{\infty} \omega_n^2 + 2 \zeta \omega_n j \omega - \omega^2}{\omega_n^2 + \frac{j \omega \chi_j}{\omega_n^2 + 2 \zeta \omega_n j \omega - \omega^2}} \right) (4)
\]

The tip deflection of the structure and the relative tip acceleration to the base acceleration in the frequency domain are calculated as:

\[
\frac{w_{tip}(\omega)}{a_b(\omega)} = \sum_{j=1}^{\infty} \frac{1}{\omega_n^2 + 2 \zeta \omega_n j \omega - \omega^2} \times \left( \frac{\sum_{j=1}^{\infty} \omega_n^2 + 2 \zeta \omega_n j \omega - \omega^2}{R \omega_n^2 + \sum_{j=1}^{\infty} \omega_n^2 + 2 \zeta \omega_n j \omega - \omega^2} \right) W_{fn}(x_{\text{end}})
\]

(5)

\[
\frac{a_{rel}(\omega)}{a_b(\omega)} = \frac{w_{tip}(\omega)}{a_b(\omega)} \ast (-\omega^2)
\]

(6)

4. Results for a case study

In this section, we study the generated energy form a 5 beam structure using the heartbeat vibrations as the source of the vibration to the system. The structure consists of five bimorph beams with 2 cm length and 0.5 cm width. PSI - S4A4E PIEZO sheets from PIEZO SYSTEMS, INC. are used as the piezoelectric element. The thickness of the brass layer and the piezoelectric layer are 0.0254 and 0.0127 cm. Each beam is connected to the next beam by a platinum rigid beam. The length of the rigid part is 0.2 cm. The tip mass is 21 grams made from platinum. A minimum safety factor of 4 is considered for the device to avoid fracture at where the beams are connected and where the first beam is clamped.

We then consider the heartbeat vibrations as the base acceleration of the system. To estimate the vibrations in the vicinity of the heart due to the heartbeat, we use the ultrasonic velocity measurements
performed by Kanai [10]. Figure 3 shows the heartbeat acceleration in time domain and frequency domain.

![Heartbeat acceleration](image1)

**Figure 3.** Heartbeat wave acceleration a) in the time domain and b) Frequency domain

By using equation (4) and equation (6) we calculate the generated voltage and power from heartbeat vibrations. The instantaneous power across a 416 kΩ purely resistive load is plotted in Figure 4. The value of the resistive load matches the resistance having the maximum power in the first natural frequency of the device. The average power for generated electricity in Figure 4 is 10.24 μW. The power needed for a pacemaker is less than 1 μW. The first natural frequency of the device occurs at 16.18 Hz which satisfies the condition of having a small natural frequency to generate more power. The assumed damping ratio in this case is 4%. Figure 5 shows different average powers for different heart rate. Although the device is linear, the output power does not change significantly with change in the heart rate.

![Power vs Time](image2)

**Figure 4.** Instantaneous power

![Output power vs heart rate](image3)

**Figure 5.** Output power for different heart rates

5. **Experimental verification**

In this section, we verify the results using experimental data. In order to do the experiment, we use a closed loop shaker and an accelerometer to measure the base acceleration. We use a laser vibrometer to measure the tip velocity of the structure. The structure is made from Aluminium and we use four steel bolts to connect the beams to the links. To verify the method, we do a sine sweep test and plot the relative tip acceleration to the base acceleration in the frequency domain. Figure 6 shows the comparison between the experimental and theoretical results for different number of beams. There is good match between the results which shows that the theoretical method predicts the natural frequency and the mode shapes of the device correctly. In our model we assume that the length of the links is much shorter than the length of the beams. Thus, there is a discrepancy between the theoretical results and the experimental results as the number of the beams increase.
Figure 6. Analytical predictions versus experimental measurements for three(a) and four(b) beams

6. Conclusion
This article presents a 3D fan-folded design to generate energy from heartbeat vibrations. The natural frequency and mode shapes of the device are found and the results are verified with experimental results. The electro-mechanical equations are solved for this configuration and the energy generated from 9 seconds of heartbeats is calculated. It is shown that the energy harvester generates enough energy to power a pacemaker. The fan-folded geometry and the tip mass makes it possible to have the energy harvester in small size (2cm by 0.5cm by 1cm). Adding the tip mass reduces the natural frequency significantly. The device can be implemented inside the body to generate the electricity needed for leadless pacemakers and makes it possible to have an autonomous pacemaker without the need of a battery.

7. References