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SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

BROAD-BANDED FREQUENCY-UP PIEZOELECTRIC-BASED ENERGY HARVESTER FROM HEARTBEATS' CYCLIC KINETIC MOTION FOR LEADLESS PACEMAKERS

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Abstract. This paper studied the kinetic heart motion for developing a self-powered leadless intracardiac pacemaker by piezoelectricity. A Doppler Laser directly at the anterior basal in the right ventricle measures the heart's kinetic motion. Piezoceramics in the cantilevered configuration are studied by finite element analysis for the power output analysis by the heart kinetic motion. The heart motion is periodic but not harmonic and is a shock-based motion. A cantilevered stopper was proposed for harvesting energy from the kinetic motion of the heart using piezoelectric (PE) materials. The study found that the energy can be harvested by applying periodic bio-movements (cardiac motion). The results also showed that adding a stopper to the PE energy harvester can generate 220 mV voltage and is less dependent on the heart kinetic motion frequency. This approach offers potential for self-powered implantable medical devices, with the harvested energy used to power devices such as pacemakers.

Keywords: Energy Harvesting, Leadless Pacemaker, Piezoelectric, Heart Motion.

1 INTRODUCTION

Cardiac pacemakers [1] can help prevent some of the 17.9 million annual deaths caused by cardiovascular diseases [2]. Conventional pacemakers, implanted in the chest and connected to the heart by leads, consist of an automatic generator, wires with electrodes, and a battery. However, these pacemakers have drawbacks such as lead dislodgement, short lifespan, and infection risk. On the contrary, intracardiac leadless pacemakers (ICLPs) are more miniature [3] and do not require leads, which eliminates many of the complications associated with conventional pacemakers [4], and also decreases the risk of infections [5]. However, ICLPs have their limitations, such as shorter battery life (approximately 10 years [6]) and the inability to retrieve them once these devices are implanted [7], [8]. Further research is needed to develop novel self-powering ICLPs to overcome these limitations. Multiple ICLPS have been implanted inside animal hearts [9]. However, multiple ICLPs implantation for humans has not been done, and inserting multiple ICLPs in human hearts is challenging. Additionally,

Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9969.444185

the psychological fear of having a low-battery level [10] and the long-term non-removability of ICLPs may limit their use, especially in younger patients [11].

The human heart produces a significant amount of kinetic energy, and harvesting this energy with high-performance piezoelectric (PE) materials could spur a medical paradigm shift. The only ICLP available on the market, Micra (Medtronic, USA), consumes small power (2 μW power [12]) and can be self-powered if a part of the heart kinetic power (0.93 W [13]) is harvested as electricity. Current energy scavenging technologies have limitations, such as solar power [14] cannot be used inside the body, electromagnetic [15] cannot be used for deep depth, triboelectricity [16] has a low lifetime, biofuel cells [17] have low power and are not genetic, and thermoelectric generators [18] can be heavy or ineffective in low body temperature-difference. Furthermore, these technologies can have a high infection risk [19]. PE ceramics are strain-sensitive with high PE coefficients. The PE effect can be created by applying mechanical stress on PE materials, which generate an electrical voltage. Periodical bio-movements were used for PE energy, blood flow [20], tissue contraction [21], and cardiac/lung motions [22], [23].

The frequency of cardiac motion is relatively low (1-3 Hz). There are other challenges for heart kinetic energy harvesting, where one is the precise measurement of the heart motion since the heart muscles do not have sinusoidal vibration and consist of a low-duty cycle [24]. Linear zigzag structure and nonlinear magnetic coupled cantilever beam were investigated for the leadless pacemaker study [25]; however, the size of these considered structures is not fit into the available leadless pacemaker. The flexible cylinder of the leadless pacemaker under the blood flow excitation has been investigated [26]; however, the tissue around this flexible structure over time will make this energy harvester ineffective. Jackson et al. [24] introduced two aluminum nitride-based MEMS rectangular cantilever beams and analyzed these beams by the simplified analytical vibration equation. The tailored curved edge cantilever MEMS beam is also investigated [27]. The space available for implanting a PE energy harvester is limited in the cardiac environment, making it challenging to design a device with enough surface area to generate sufficient energy. The materials used in the energy harvester must be biocompatible to ensure they do not cause an immune response or tissue damage when implanted in the body. The encapsulation of an energy harvester is one of the solutions since the leadless pacemaker has already been designed with a biocompatible shell.

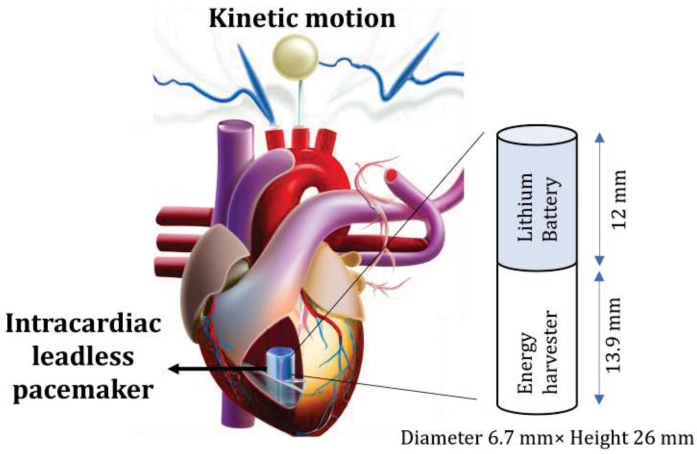

Figure 1: Intracardiac leadless pacemaker and the heart kinetic-based energy harvesting concept.

This paper aims to assess the heart kinetic energy harvesting for leadless pacemakers by a conceptual approach for integrating PE energy harvesters into commercial leadless pacemakers, see **Figure 1**. First, a laser sensor directly measures the precise heart kinetic motion during animal surgery. Second, the power output from piezoelectric materials is investigated using a small-volume PE energy harvester. The heart motion results act as the guideline dynamic analysis for piezoelectricity, and the energy generator results indicate the energy harvesting for advanced self-power leadless pacemakers.

2. HEART KINETIC MOTION

The human heart's kinetic motion, amplitude, and motion shape can present valuable data for designing energy harvesters; however, the precise data on the heart's motion type and amplitude are challenging. The heart is a complex organ having both electrical and mechanical indexes. The electrocardiogram (ECG), a common diagnostic tool, is the electrical activity measurement of the heart. Mechanical kinetic motion of the heart, which refers to the movement of the heart muscles, can provide valuable information about heart function. Electrical and dynamic heart motions show similarities and characteristics as a complete analysis of heart activities. ECG signals are employed from the literature, but since the heart dynamic motion database is limited, animal surgery tests on a living pig's heart are carried out.

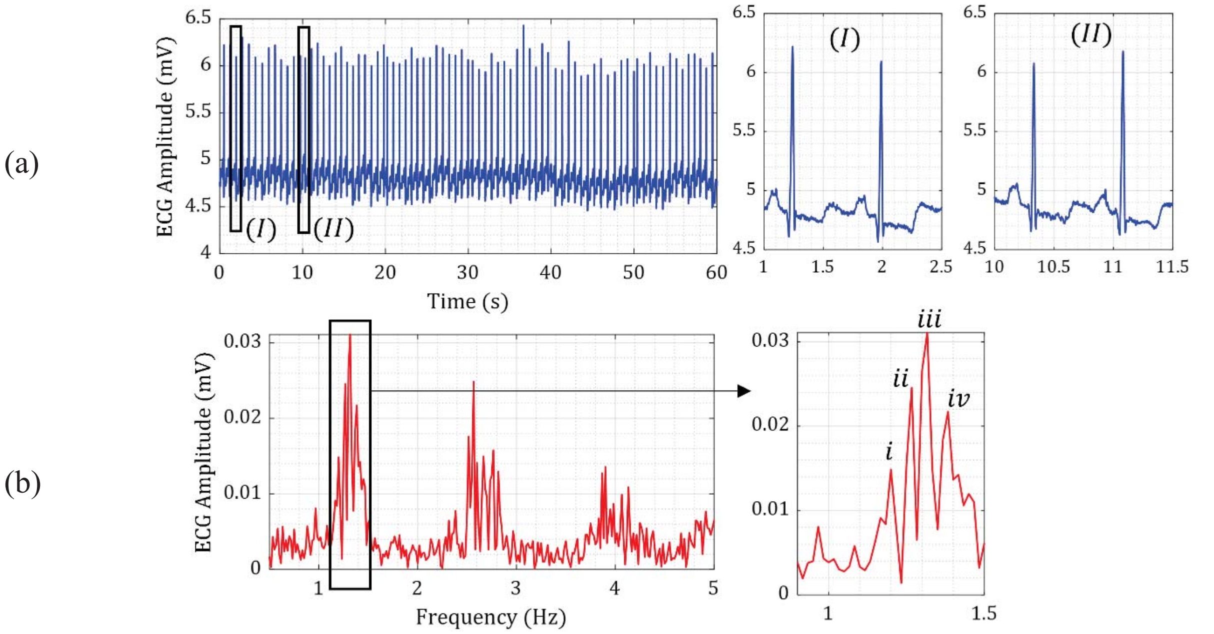

Figure 2: (a) ECG signal from a 69-old male patient with normal sinus rhythm [28] with zoomed-in views at two 1.5-s time intervals and (b) the Fourier Transform of the ECG and the zoomed-in view around typical heart rate frequencies

ECG open datasets are vastly available [28]. **Figure 2** (a) and (b) shows the time and frequency domain signals of ECG measurement of a 69-year-old male volunteer [28]. The ECG signal during 60 seconds for one patient shows that the amplitude of ECG is slightly variable, see **Figure 2** (a). This variation is further illustrated in the zoomed-in views of the ECG signals in **Figure 2** (a)-I and **Figure 2** (a)-II. Nevertheless, the similarity of all ECG signals is the shock pattern in the ECG signal, demonstrating the sudden motion of the heart in a short period. The frequency domain ECG signals in **Figure 2** (b) show that the heart rate changes slightly between 1.2 Hz to 1.38 Hz even for 60 seconds.

For the mechanical heart muscle movement measurement, the animal surgery measurements are carried out for in vivo kinetic heart motion by a Doppler laser displacement meter, type ILD1320-50mm from MICRO-EPSION, measuring the displacement by a sampling rate of 2000 Hz. A fixed-based frame kept the laser facing down to the middle line of a beating female pig's heart. Animal treatment was under the Danish Animal Experiments Inspectorate's requirements, and this institution approved the study (no. 2021-15-0201-0082). The animal was a 35 kg-female pig with one week of acclimation.

The direct heart measurement was implemented in the sagittal plane during open heart surgery (**Figure 3** (a)). The pig's heart rate was ~160 beats per minute (BPM) during the animal test due to atrial fibrillation. Figure 3 (a) shows the heart measuring point in the Coronal plane. The heart displacement during 11 cardiac cycles with 1660 BPM is shown in **Figure 3** (a). Like the ECG signal, the direct laser displacement shows a high-amplitude short-duty cycle half-wave motion and a low-amplitude sinusoidal motion. The breathing also creates a ~0.25 Hz frequency motion of the heart, as shown in **Figure 3** (a). Therefore, the heart's kinetic motion consists of respiratory and heart-beating motion. The maximum heart movement for the cycles is ~22 mm. However, excluding the respiratory motion, the heart motion by the heart beating only is ~12.8 mm. A smoothening version of these cycles is used for computer simulation of energy harvesters (**Figure 3** (a)), as transient solutions require a smooth input function.

For comparison, the kinetic heart measurement using an endoscopic monocular vision system of a porcine model of 25 kg is shown in **Figure 3** (b) from Sauvee et al. [29]. This study used two attaching patches to the outer muscles of the heart. Measurements of heart displacement are shown in **Figure 3** (b). The respiratory-induced heart and heart-beating motions are visible in this study as well. Nevertheless, the Sauvee's heart-beating movement result is not as uniform as the direct measurement in this study's animal testing. Therefore, these presented laser measurements provide valuable inputs for the dynamic analysis of the heart, especially for energy harvesting technologies. Moreover, the shock-based large-amplitude heart movement can be seen in **Figure 3** (a), which lasts approximately 40% of the cardiac cycle. The shock-based motion is like the ECG signal; however, the duration of the dynamic movement is longer than the ECG signal.

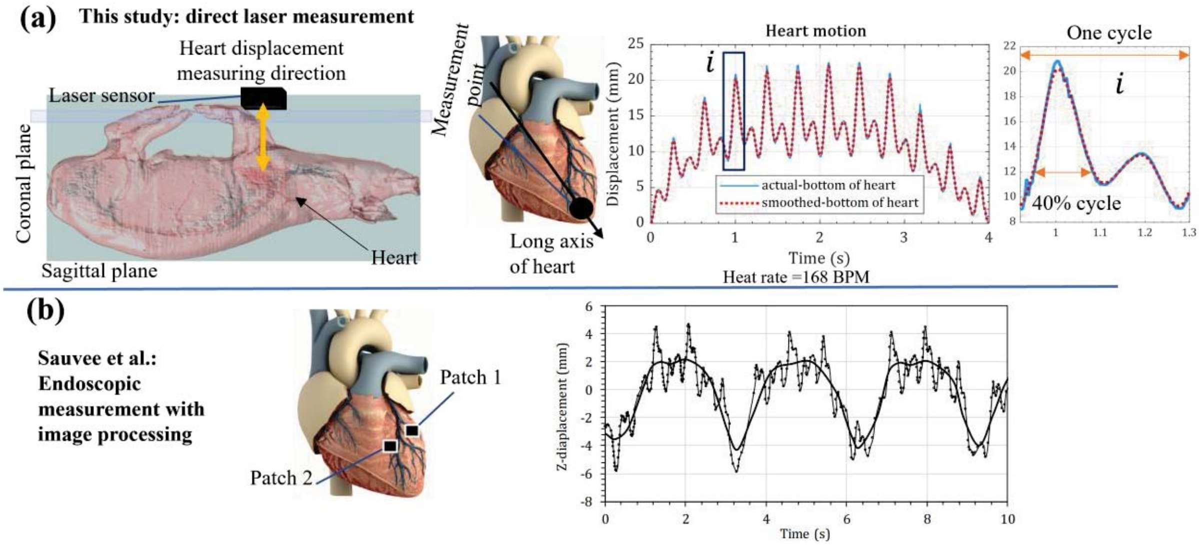

Figure 3: The kinetic heart motion during heart beating and respiratory, (a) direct laser measurement of the lower point of the heart in the mid-line, and (b) by endoscopic measurement with two attaching patches by Sauvee et al. [29].

The ECG has many small fluctuations in the signal compared to the mechanically measured heart motion. The ECG signal presents valuable information about the heart's electrical function, even though the limitation is the missing point between the electrical function of the heart and the mechanical motion. Therefore, the heart's kinetic motion is essential for energy-harvesting applications.

3 PIEZOELECTRIC ENERGY HARVESTING ANALYSIS

A cantilevered energy harvester, the most widely used boundary condition in energy harvesting [30], was studied. The cantilevered energy harvester was a bimorph, two PZT-5A piezoelectric layers, a titanium center shim, and an added tip mass. The outer cylindrical shell of the leadless pacemakers is made of titanium, which is moisture-resistant and biocompatible with the tissues. Thus, using the lead-based ceramic piezoelectric material is not critical; however, the recent advanced in lead-free materials proposed high-performance lead-free materials as alternatives [31]. Studies were carried out by finite element analysis using COMSOL Multiphysics version 6.1, with transient solutions with the real-time heart displacement measurements in Section 2.

An intracardial leadless pacemaker was conceptually modified so that an energy harvester replaced the main bulky battery, see **Figure 4** (a). The dimensions of the energy harvester are shown in **Figure 4** (b). The ECG signals demonstrate that a patient's heart rate can vary slightly. A stopper is also considered to create a nonlinear impact at the energy harvester tip for presenting a broadband energy harvester. **Figure 4** (c) shows the stopper. The cantilever beam's two first vibration modes and natural frequencies are given in **Figure 4** (d).

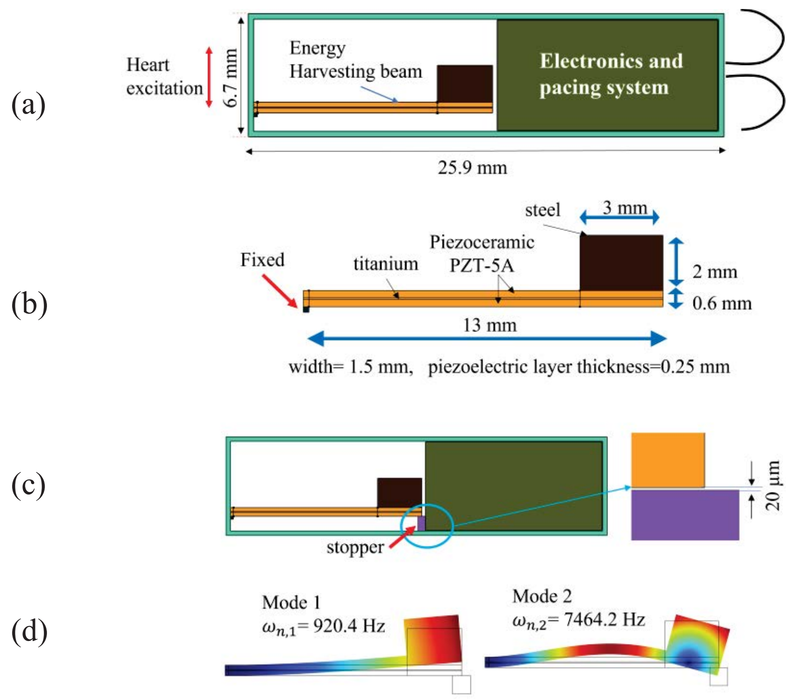

Figure 4: (a) The intracardiac leadless pacemaker with an energy harvesting beam, (b) dimensions of the energy harvester, (c) adding a stopper for creating a broadband frequency energy harvester, (d) the first two bending modes and natural frequencies of the cantilever beam.

The heart's kinetic motion was measured during an animal open heart surgery, and the performance of a piezoelectric harvester was evaluated. First, the transient analysis obtained the mechanical deformation under heart motion. Then, this periodic beam deformation at the harvester's tip with different frequencies and with and without a stopper was analyzed. The mechanical damping coefficients for both cases are considered to be 2%.

Figure 5 shows the mechanical performance of the cantilevered beam under the heart input kinetic motion. The transient analysis was conducted during the 0-4 s period, considering the respiratory and heart beating motions, **Figure 5** (a). The von Mises stress and strain are illustrated in **Figure 5** (b)-(d), respectively, at two spots, *i.* t=0.12 s and *ii*. t=0.26 s. The maximum von Mises stress was ~250 kPa, and the maximum first principal strain was ~4 με (ε: strain). The tip deformation under this heart kinetic energy was 0.2 μm < ε < 0.4 μm.

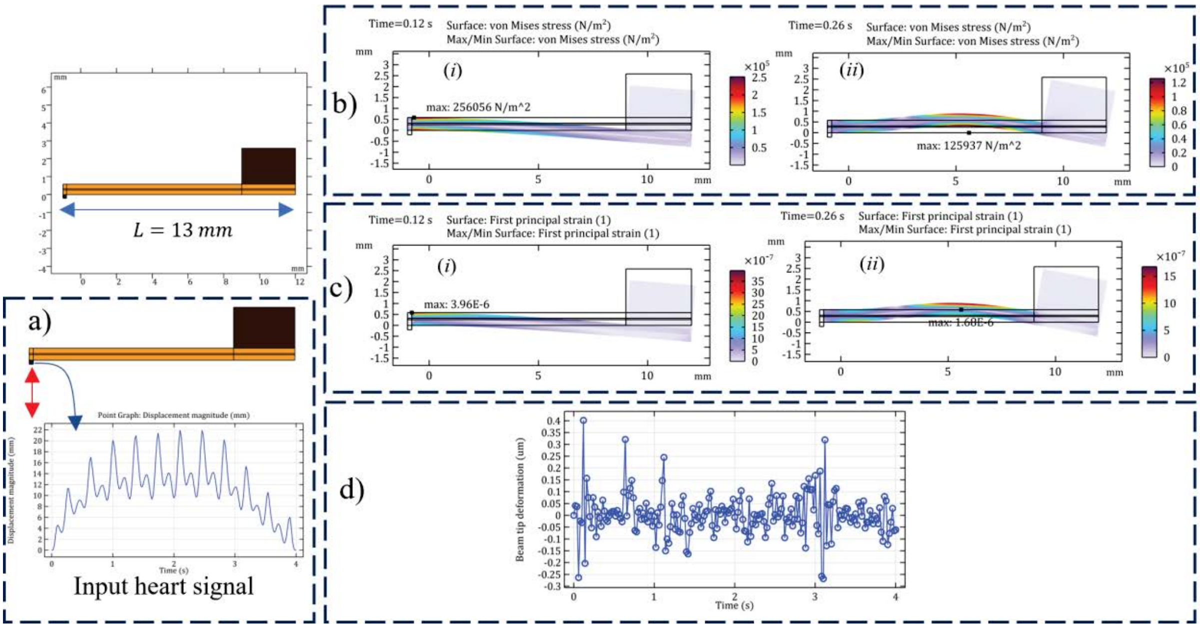

Figure 5: The piezoelectric cantilevered beam mechanical response under heart kinetic motion, (a) the kinetic heart motion applied to the energy harvester during 0-4 s, (b) surface von Mises stress for *i*. t=0.16 s and *ii*.t=0.26 s, (c) surface first principal strain for *i*. t=0.16 s and *ii*. t=0.26 s, and (d) beam tip deformation under the applied heart kinetic motion.

The mechanical and electrical performance of the PE beam without the stopper is shown in **Figure 6** (a) and with the stopper in **Figure 6** (b). When the PE beam was deformed by a 0.3μm deformation at 1 Hz frequency, the output PE voltage was ~0.8 mV. The von Mises stress, first principal strain, and the electrical potential are shown in **Figure 6** for the peak of the tip deformation. By adding the stopper, **Figure 6** (b), there was an impact between the piezoelectric tip and stopper, which considerably excited the piezoelectric beam toward higher voltage outputs. As shown in **Figure 6** (b), the voltage output by the stopper was around 220 mV, considerably higher than the non-stopper case. Changing the frequency of tip deformation does not considerably change the peak voltage generation. Therefore, adding the stopper created a broadband voltage spectrum so that the output voltage was less dependent on the input heart rate.

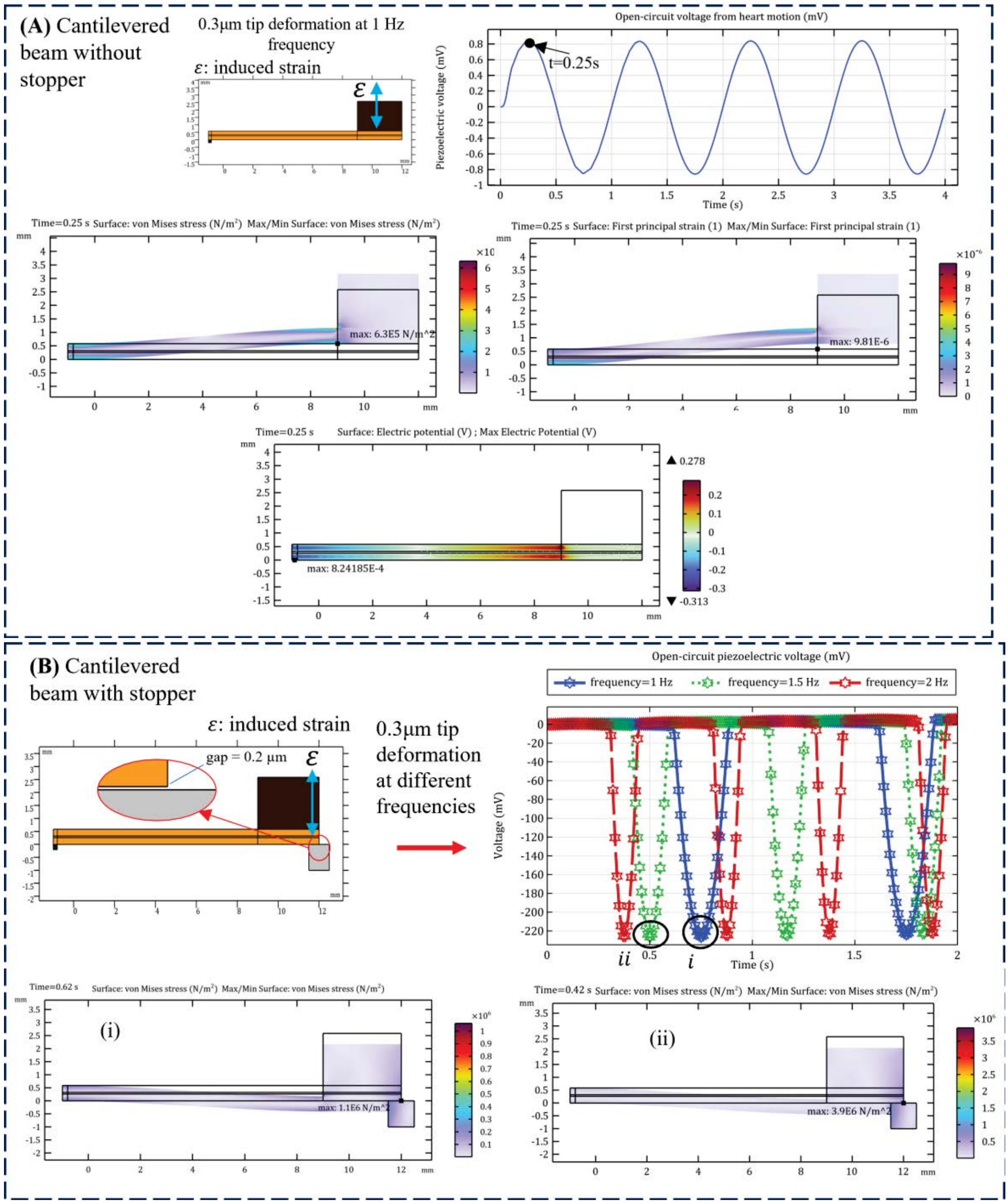

Figure 6: (A) The cantilevered beam harvester without stopper under a periodic 0.3μm induced strain from the heart motion at 1 Hz frequency, demonstrating the piezoelectric voltage over time, and von Mises stress, First principal strain, and electric potential at t=0.25 s, and (b) the cantilevered beam with stopper under a periodic 0.3μm induced strain from the heart kinetic motion, demonstrating piezoelectric voltage with input frequencies of 1 Hz, 1.5 Hz, and 2 Hz, and the von Mises stress during the impact between the stopper and the piezoelectric beam at *i*. 1 Hz frequency and *ii*. 1.5 Hz frequency.

4. CONCLUSION

The prospect of piezoelectric energy generation by the heart's kinetic motion is presented toward the self-powering of leadless pacemakers. The investigated prospects include the kinetic motion of a pig's heart in an animal surgery trial test and electromechanically finite element analysis of piezoelectric energy harvesters. Heart motion has a high-level shock-inducing motion, leading to the main piezoelectric power generation and a low-level sinusoidal motion. A stopper impact-based cantilevered beam is reported, demonstrating better performance. This impact-based has less frequency dependency on the heart frequency motion. Our team currently explores this concept for self-powering medical devices. Power analysis by different resistance loads, power optimization under stopper conditions, and experimental studies are proposed as future works.

Acknowledgment

The authors thank Ali Asghar Enkeshafi, a technology developer from Aalborg University AAU Energy, for supporting experimental setup and manufacturing. The authors also thank Associate Professor Dr. Benedict Kjærgaard from Aalborg University Hospital, Denmark, for his help and support during the animal study. This research is partially financed by the Independent Research Fund Denmark International Post-doc grant under grant number 1031-00001B and the Lundbeck LF-Experiment E-Help project with the grant under grant number R324-2019-1747.

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