A PIEZOELECTRIC FREQUENCY-INCREASED POWER GENERATOR FOR SCAVENGING LOW-FREQUENCY AMBIENT VIBRATION

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ABSTRACT

This paper presents the design, fabrication, and testing of a piezoelectric inertial micro power generator for scavenging low-frequency non-periodic vibrations. A mechanism up-converts the ambient vibration frequency to a higher internal operation frequency, in order to achieve better electromechanical coupling and efficiency: enhancing the generators performance at very low frequencies (<30Hz). The generator incorporates a bulk piezoelectric ceramic machined using ultrafast laser ablation. The fabricated device generated a peak power of 100µW and an average power of 3.25µW from an input acceleration of 9.8m/s² at 10Hz. The device operates over a frequency range of 24Hz. The internal volume of the generator is 1.2cm³.

INTRODUCTION

Rapid advances in silicon-based wireless microsystems technology over the past few decades has led to devices with unprecedented performance and utility with low power consumption. These technological advancements have led to the recent pervasiveness of wireless technology. However, for these systems to truly become ubiquitous, the issue of power has to be addressed. Batteries power most of these devices. However, they typically cannot last the entire lifetime of the device, and periodic replacement or recharging is needed. This is preventing different applications of wireless devices from being feasible.

Energy scavenging from ambient sources can enable many new uses for wireless microsystems. While several ambient energy sources have been explored, kinetic energy is one of the most prevalent [1, 2]. However, the vast majority of the reported devices are designed to operate at mechanical resonance and at high frequencies (>30Hz), limiting them to scavenging vibrations from periodic sources such as motors and other man made machinery. This leaves out a number of applications that are prime candidates for energy scavenging such as wearable or implantable devices, environmental monitoring applications, wireless devices for agriculture, and various security and military uses. This is because the kinetic energy in these applications is not periodic and occurs less often. This paper presents the design, fabrication, and testing of a piezoelectric inertial micro power generator, Figure 1, for scavenging low-frequency non-periodic vibrations. This is the first micro-scale piezoelectric generator reported capable of ≤10Hz operation. It implements the Parametric Frequency Increased Generator (PFIG) architecture, previously demonstrated using a bench-top prototype [3], followed by a miniaturized electromagnetic generator [4]. The PFIG architecture was developed to specifically address the characteristics of low-frequency vibrations. Resonant low-frequency scavengers require a large internal displacement range to accommodate big vibration amplitudes, while the PFIG architecture allows for this range to be designed and kept as small as necessary – improving the power density, and enabling MEMS integration. This is highlighted in this paper by incorporating a brittle bulk piezoelectric ceramic (max. 1000µ strain). Additional benefits of piezoelectric transduction include: reduced volume (halved compared to [4]), large rectifiable voltage, and the possibility of combining piezoelectric and electromagnetic transduction mechanisms into a single generator.

DESIGN

The parametric generator is a non-resonant architecture [3] where a bi-stable mechanical structure is used to initiate high-frequency mechanical oscillations in an electromechanical scavenger. The operation of the PFIG generator is shown in Figure 2 (cross sectional view along the length of the generator). Two Frequency Increased Generators (FIG) are oriented to face each other. The FIG is a piezoelectric bimorph harvester that has a resonant frequency 100x larger than the targeted input vibrations. Each FIG is outfitted with a small NdFeB magnet which is used for magnetic latching with the inertial mass and actuating the FIG. A large tungsten-carbide inertial mass is suspended in the middle on a compliant spring. The PFIG operation is outlined in...
Figure 2. a) PFIG architecture. b) The generator is depicted at three instances of time during an incident displacement.

Figure 2b. The generator operates such that the inertial mass snaps back and forth between the two FIGs - latching magnetically each time. As the mass moves it pulls the FIG spring along. This action transfers mechanical energy from the inertial mass and stores it in the FIG spring. As the forces on the FIG spring overwhelm the holding magnetic force, the inertial mass detaches and is pulled to the opposing FIG. The freed device now resonates at its high natural frequency converting the stored mechanical energy to electrical. By up-converting the ambient vibration frequency to a higher internal operation frequency, the PFIG generator is able to achieve better electromechanical coupling and efficiency. This is referred to as frequency up-conversion [5]. This entire process is subsequently repeated in the opposite direction and the inertial mass moves from FIG to FIG as long as there is sufficient ambient kinetic energy available.

The piezoelectric FIG is designed as a clamped-clamped bimorph beam operating in the 31-mode. This mode of operation offers weaker coupling coefficients, however larger strains can be achieved with a weaker force because of the more compliant configuration. To further decrease the spring constant of the structure while limiting the footprint of the device, the beam is shaped as a spiral. The two arms on the end of the spiral are designed with a linearly increasing cross-section [6], widening as it moves from the spiral toward the clamped end. This way the high stress concentration at the clamped end is alleviated, improving reliability, and film stress is more evenly distributed across the spiral arms, utilizing more of the PZT material for energy conversion. A commercial lead zirconate titanate (PZT) bimorph is used consisting of a brass shim sandwiched between two sheets of PZT-5A4E, with PZT/Brass/PZT thickness of 130/130/130µm.

In order to design the FIG spiral, coupled field finite element modeling is performed using ANSYS™, and the influence of a number of geometric properties is investigated. Those include the width w, arm length l_a, and thickness of the PZT layers t_p, as well as the number of turns n, the gap between adjacent spiral turns g_o, and electrode placement l_c. A fixed force in the center, mimicking the one applied by the inertial mass, is used to simulate FIG actuation. In these simulations all but one of the variables are held at a constant baseline while the influence of that one is determined. Simulation results studying the influence of the various parameters are presented in Figures 3-5.

In Figure 3, the influence of the spiral gap g_o and beam width w is shown. When the gap increases the spring constant decreases, because the overall spiral length increases (the number of turns is kept fixed). As the stiffness increases, the deflection and consequently the stress for a given force decreases, and power drops. The widening of the spiral also plays a similar role. As the beam widens the stiffness increases and the stress...
in the beam increases, increasing the scavenged power. However, an optimum point exists because the increasing spring constant ultimately limits the beam deflection. The widening of the arm cross-section is modeled by \( \Theta \), the angle made by the spiral arm with its centerline. In all cases the power drops as \( \Theta \) increases because of a reduction in the maximum stress in the beam.

The thickness \( t_p \) of the PZT layer is a very important parameter and its influence is shown in Figure 4. One can see that an optimal thickness exists, once again caused by the interplay between spring constant, stress, and deflection. Lastly, Figure 5 shows the stress distribution along the two arms of the spiral as the cross section is changed. As expected, when the arm becomes gradually wider from center to base, the stress distribution becomes more linear, making the FIG more reliable. The optimal electrode configuration occurs when they are placed only above the spiral arms \( l_e=\ell_e \). Due to the torsional motion associated with the spiral deflection, electrodes placed on the spiral itself will reduce the power due to alternating polarization.

**FABRICATION**

Figure 6a shows an image of the manufactured FIG generator. The generator housing is milled out of aluminum. It consists of four separate parts, bolted together during assembly, clamping down the spring suspensions in the process. The spring for the inertial mass is fabricated out of 127\( \mu \)m thick copper alloy 110. The copper sheets are mounted on carrier silicon wafers using photoresist, lithographically patterned, and immersion etched in FeCl\(_3\) at 45\(^\circ\)C. The inertial mass is made out of two tungsten carbide pieces, machined using electric discharge machining (EDM), and bonded to the spring suspension on either side atop a 1\( \mu \)m spacer.

For some of the FIGs the PZT layer is ground down to 40\( \mu \)m on both sides using a lapper, and Cr/Au electrodes are evaporated. The piezoelectric bimorph is then machined using a Ti-Sapphire femto-second laser (wavelength of 780nm) with a 150fs pulse duration and a 1kHz repetition rate. In order to enable complex shape patterning and automated machining of several samples in a serial process, the pieces are placed on a computer controlled XYZ-\( \Phi \) motion stage, on which the laser beam is focused through a shutter. Compared to other bulk PZT substrate patterning technologies, femto-second laser machining provides a small feature size with a high aspect ratio, minimum undercut, and less damage to the material. In order to keep stress low, and for structural rigidity reasons the spiral was designed with a width of \( w=500\mu \)m and gap of \( g=50\mu \)m, which after machining resulted in 470\( \mu \)m and 80\( \mu \)m respectively. The arm length \( l_\ell=5\)mm; the maximum which could fit in the casing. Due to space constraints, the spiral was also designed with 2 turns. A finished FIG spiral is shown in Figure 6b. NdFeB magnets are adhered to the spiral center using cyanoacrylate.

**RESULTS**

Table 1 shows a summary of the various designed and measured FIG parameters. Two types of FIGs were used, one set having the full 130/130/130\( \mu \)m thickness and one set where each PZT side was lapped down to a thickness of 40\( \mu \)m. Initial testing was performed to characterize the FIG devices. Each FIG was mounted on a shaker table and the resonance frequency was found. They were then actuated at resonance while the load impedance was varied in order to determine the optimal load impedance. This data is included in Table 1. The FIG is assembled, and tested at a number of amplitudes (minimum operating threshold for this design is 6.86m/s\(^2\)). The minimum frequency at which the generator can be tested accurately is 10Hz due to limitations associated with the vibration test system. Each FIG is loaded with its optimal impedance and the voltage across this impedance is monitored. Figure 7 shows the operation of the FIG. By looking at the voltage waveform it becomes evident where the inertial mass attaches to each FIG, and where the mass detaches and travels to the opposing device. Considerable non-linearity can be noticed, caused by the large bimorph deflections. The full thickness FIGs generated 3.25\( \mu \)W of average power when actuated at 1g with a frequency of 10Hz, while the thinned down samples produced 2.44\( \mu \)W from the same input. It was expected that thinning down the PZT FIGs can increase the generated power significantly. However, in this first attempt the FIGs containing the thinned bimorphs produced less power. This is likely due to one of several factors including, micro-cracks developing during lapping, roughness and poor electrical contact, and/or excessive heating.

| Inertial Mass k | Width w | Gap g | Arm \( l_e \) | Inert. Mass \( m \) | Θ | Thick. \( \ell_e \) | Z(
\text{thick, thin}) | \( f_e \) (thick, thin) | Spiral \# | Q\(_{\text{ua}}\) (thick, thin) | 1° |
<table>
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<td>80µm</td>
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<td>135N/m</td>
<td>1°</td>
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<td>187, 161Ω</td>
<td>611, 975Hz</td>
<td>2</td>
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*Table I: FIG Summary*
will focus on increasing the PFIG power density, PFIG, while reducing the volume by half. Performance set by the previous electromagnetic density of $2.7 \mu W/cm^3$ actuated at $9.8m/s^2$ capable of producing $3.25 \mu W$ of average power when actuated at $10Hz$ or less in Table 2.

**CONCLUSION**

This paper reports on the design, fabrication, and testing of a micro piezoelectric PFIG generator capable of producing $3.25\mu W$ of average power when actuated at $9.8m/s^2$ at $10Hz$. This gives a power density of $2.7\mu W/cm^3$, matching the state-of-the-art performance set by the previous electromagnetic PFIG, while reducing the volume by half. Future work will focus on increasing the PFIG power density, including better latching and higher mechanical energy transfer into the FIGs, as well as improving the PZT thinning process.

**ACKNOWLEDGEMENTS**

This project is supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866. The authors thank Sandia National Laboratories for fellowship support. The authors thank Dr. Becky Peterson for her valuable contributions.

**REFERENCES**


**Table II. Performance Comparison**

<table>
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<th>Ref</th>
<th>Input Acc. (g)</th>
<th>Input Freq. (Hz)</th>
<th>Vol. (cm$^3$)</th>
<th>Peak Power (µW)</th>
<th>Avg. Power (µW)</th>
<th>Pow. Dens. (µW/cm$^3$)</th>
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$^*$ Denotes This Work, $^t$ Denotes functional volume