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Energy Scavenging From Environmental Vibration

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Energy Scavenging From Environmental Vibrations

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Abstract

The goal of this project is to develop an efficient energy scavenger for converting ambient low-frequency vibrations into electrical power. In order to achieve this a novel inertial micro power generator architecture has been developed that utilizes the bi-stable motion of a mechanical mass to convert a broad range of low-frequency (<30Hz), and large-deflection (>250µm) ambient vibrations into high-frequency electrical output energy. The generator incorporates a bi-stable mechanical structure to initiate high-frequency mechanical oscillations in an electromagnetic scavenger. This frequency up-conversion technique enhances the electromechanical coupling and increases the generated power. This architecture is called the Parametric Frequency Increased Generator (PFIG). Three generations of the device have been fabricated. It was first demonstrated using a larger bench-top prototype that had a functional volume of 3.7cm3. It generated a peak power of 558µW and an average power of 39.5µW at an input acceleration of 1g applied at 10 Hz. The performance of this device has still not been matched by any other reported work. It yielded the best power density and efficiency for any scavenger operating from low-frequency (<10Hz) vibrations. A second-generation device was then fabricated. It generated a peak power of 288µW and an average power of 5.8µW from an input acceleration of $9.8m/s^2$ at 10Hz. The device operates over a frequency range of 20Hz. The internal volume of the generator is $2.1cm^3$ ($3.7cm^3$ including casing), half of a standard AA battery. Lastly, a piezoelectric version of the PFIG is currently being developed. This device clearly demonstrates one of the key features of the PFIG architecture, namely that it is suitable for MEMS integration, more so than resonant generators, by incorporating a brittle bulk piezoelectric ceramic. This is the first micro-scale piezoelectric generator capable of <10Hz operation. The fabricated device currently generates a peak power of 25.9µW and an average power of 1.21µW from an input acceleration of $9.8m/s^-$ at 10Hz. The device operates over a frequency range of 23Hz. The internal volume of the generator is $1.2cm^3$.

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Introduction

In today's world of ever increasing ambient intelligence, a number of benefits can be realized by meeting the energy demands of these microelectronic systems by scavenging energy from their surroundings. Eliminating maintenance and battery replacement enables many long-lifetime applications both technically, and from the standpoint of cost. One of the most abundant energy sources is ambient motion, and over the past few years a great deal of research has gone into developing ways to use it effectively. A vast majority of this research has been aimed at utilizing resonant systems to scavenge high frequency periodic vibrations from machines or other man made sources. However, little attention has been devoted to developing efficient methods to scavenge energy from low-frequency non-periodic motion. This is important in applications such as wearable and implantable devices, environmental monitoring, agricultural applications, and security and military uses.

Motivation and Design

A typical inertial power generator employs a mass suspended within a frame that performs work against a damping transduction force as it moves relative to the frame. This type of generator performs optimally when operated at its resonant frequency. However, two problems prevent this approach from being applied to low-frequency vibrations: 1) as the frequency drops so does the expected power density, and 2) most low-frequency vibrations are caused by environmental sources and are not periodic. One of the two factors contributing to the decrease in power density and efficiency associated with low-frequency vibrations is the increase in the required spatial displacement (and thus volume) of the generator. Resonant generators need to have an internal displacement greater than the external vibration amplitude. Secondly, velocity damped generators, which include electromagnetic and piezoelectric devices, will produce a weaker damping force. In other words, they will have weaker electromechanical coupling, as the frequency (and velocity) drops.

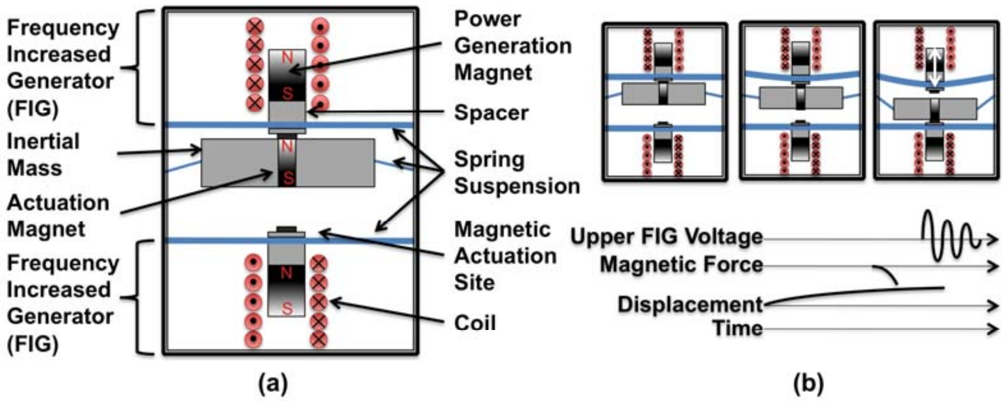
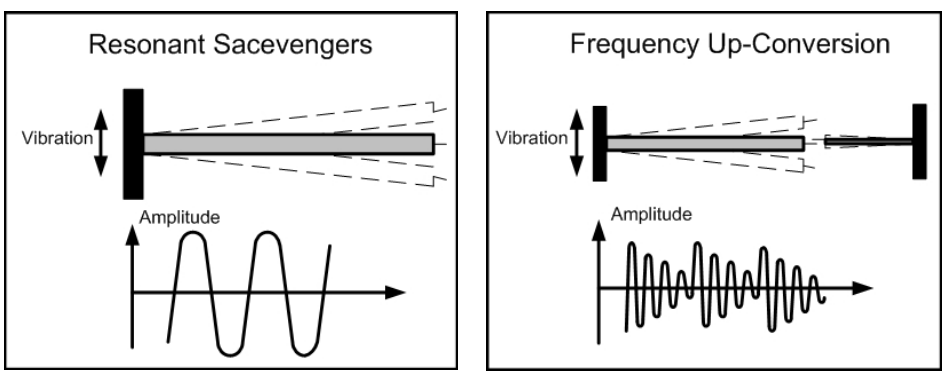


Figure 1: a) Illustration of the PFIG generator architecture. b) Theory of operation - the generator is depicted at three instances of time during an incident displacement

To address these challenges a non-resonant Parametric Frequency Increased Generator (PFIG) has been developed and tested. The PFIG architecture is shown in Figure 1a. An inertial mass is used to couple energy from the ambient, and store it in the spring of one of two Frequency Increased Generators (FIG) located above and below the mass. The FIG can then convert this mechanical energy to electrical at a later time. Two FIGs are oriented to face each other. The FIG is an electromagnetic harvester which has a resonant frequency at least 10x larger than the targeted environmental vibrations. Each FIG is outfitted with a ferromagnetic pad that can provide an attractive force to a nearby magnet. In the middle is the inertial mass, which is suspended to the frame on a compliant spring, mainly for structural integrity. Two NdFeB magnets are placed on either side of the mass. The operation of the PFIG is outlined in Figure 1b. The generator operates such that the inertial mass snaps back and forth between the two FIG generators and attaches to the ferromagnetic site. As shown in Figure 1b, as the mass moves due to induced frame motion, it pulls the FIG spring with it, storing energy. As the inertial mass approaches the opposing FIG, the magnetic force of attraction begins to increase. A time is reached where the forces acting on the FIG overwhelm the magnetic force holding the inertial mass attached – and it is pulled to the opposing FIG. The freed device now resonates at its high natural frequency converting the stored mechanical energy to electrical. This process is subsequently repeated in the opposite direction.

The FIG component of the proposed architecture gets its name from a concept called frequency up-conversion [1] a method to increase the effectiveness of low-frequency scavengers. Since the electrical damping force is proportional to velocity, it is advantageous to implement a mechanical conversion such that the internal resonant frequency of the generator is increased over the input frequency. The damping force is thereby scaled proportionately. The frequency up-conversion principle is illustrated in Figure 2.



(a) (b)

Figure 2. (a) Illustration of simple mass-spring-damper resonant micro generators, (b) illustration of frequency up-conversion.

Electromagnetic PFIG Development

Two prototype PFIG generators [2,3] were fabricated and assembled to test out the proposed architecture. Spring suspensions for both the FIG and the inertial mass are fabricated out of 127μm thick copper alloy 110. The copper sheets are mounted on carrier silicon wafers using photoresist, lithographically patterned, and immersion etched in FeCl2 at 45°C. NdFeB magnets are bonded to the inertial mass and FIG springs using cyanoacrylate. Coils are wound from 50μm diameter enameled copper wire. In the first generation device, FIG components are mounted within a specially machined acrylic housing, and the spring is clamped in place using a screwed in aluminum ring. The PFIG generator is put together on a hybrid assembly, such that each of the three components can be moved in the z-direction using a micropositioner. This assembly gives flexibility in interchanging components, characterizing the influence of and optimizing various parameters, and validating theoretical modeling of the system. The fabricated test setup and mounted PFIG are shown in Figure 3a. Figure 3b shows a close-up of one of the FIG cases revealing the coils, magnet, and assembled device. The entire test jig is mounted on a shaker system for vibration testing.

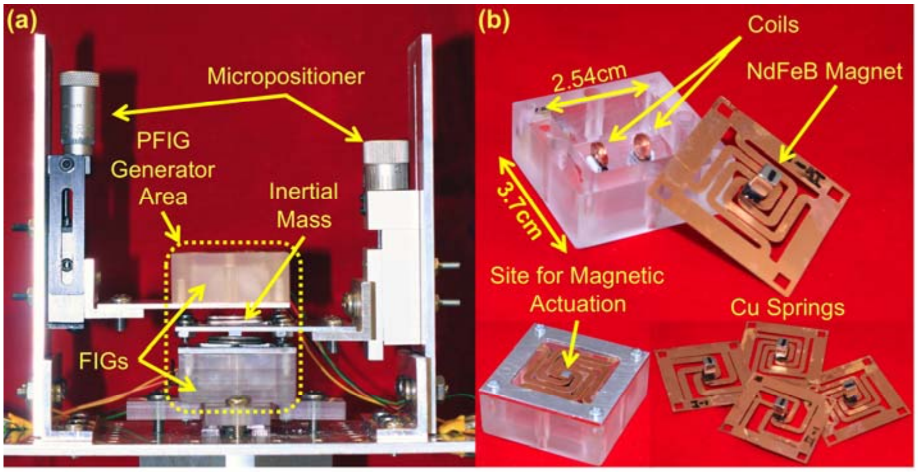
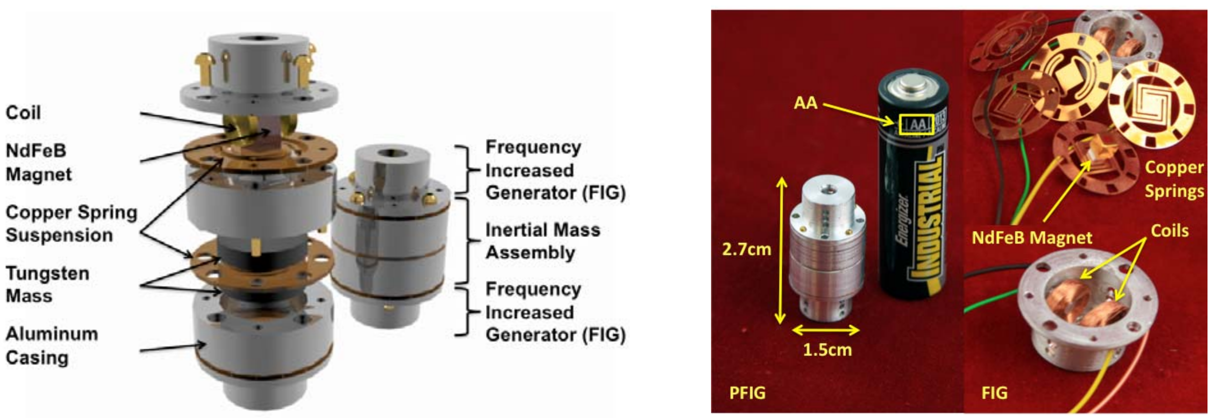


Figure 3. a) Photograph of the assembled Gen 1 parametric generator and test setup. The top Frequency Increased Generator (FIG) and the inertial mass are mounted on micropositioners to freely tune the displacement gap. b) Detailed view of one of FIG components.

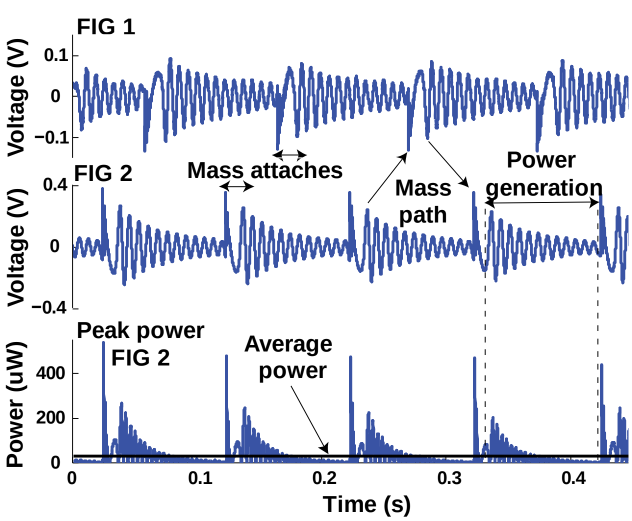


(a) *(b)*

Figure 4. a) Illustration describing the developed Gen 2 Parametric Frequency Increased Generator (PFIG). b) Photograph of the fabricated PFIG. On the left, the PFIG device is compared with a standard AA battery. On the right, a close-up of one of the FIGs is shown, along with an assortment of etched copper springs.

The second generation PFIG device is manufactured in a similar way. Namely the spring suspensions are made using lithography and etching. 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 1mm spacer. Lastly, all of the components are placed within a specialized aluminum housing. Fig 2a shows an illustration of the manufactured device, while the left side of Fig 4b shows the assembled 2nd generation PFIG next to a standard AA-size battery, while the right side of the figure shows the inside of one of the FIG casings along with an assortment of etched copper springs.

Testing of the electromagnetic PFIG devices was carried out on a shaker table. The PFIGs are assembled, and tested at 1g. The minimum frequency at which the generators can be tested accurately is 10Hz due to limitations associated with the vibration test system. Fig 5a shows the operation of the Gen 1 PFIG. The top two plots show the voltage generated by each FIG across the load, and the bottom plot shows the instantaneous power from FIG 2. 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. The bandwidth of the PFIG device is determined by the resonant frequency of the inertial mass and its spring suspension. To determine this cutoff, the PFIG input frequency is increased until it stops functioning. It was found that the Gen 1 device generator could function up to a frequency of 20Hz (21Hz for Gen2). Figure 5b shows a frequency response plot for the first generation PFIG.



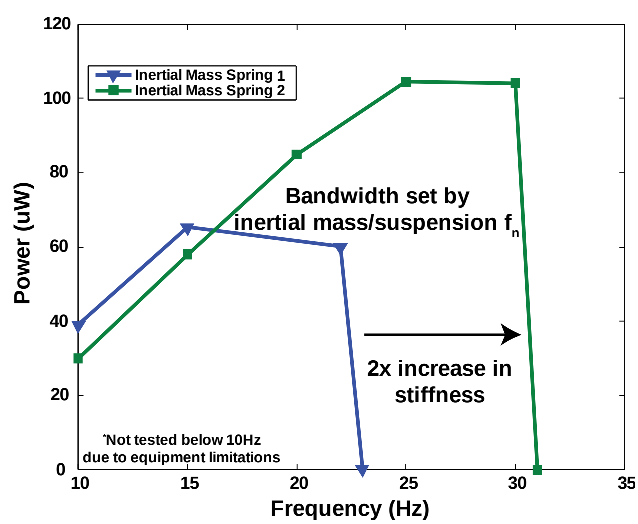


Figure 5 a) Oscilloscope trace showing the Gen 1 parametric generator operation from an external acceleration of 1g at 10 Hz. The top and bottom voltage waveforms correspond to the top and bottom FIG devices as the inertial mass snaps back and forth between them. The bottom plots shows instantaneous power from FIG 2. b) Measured frequency response of the Gen 1 PFIG generator. The cut-off frequency is determined by the inertial mass/spring suspension natural frequency. By altering the suspension stiffness the bandwidth can be increased to a suitable value. Input acceleration is 1g at 10 Hz.

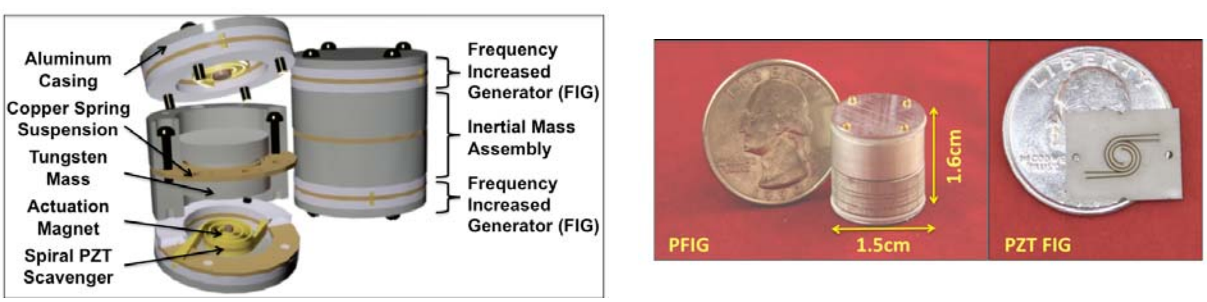
A performance comparison of the Gen 1 and Gen 2 devices is shown in Table 1, comparing them to all previously reported efforts in the frequency span of <10Hz. The two PFIG generations define the state-of-the-art in scavenging low-frequency vibrations. Current efforts are underway to improve their performance and further integrate these devices.

Table I. Performance Comparison	Input Accel. (g)	Input Freq. (Hz)	Volume (cm^3)	Peak Power (μW)	Avg. Power (μW)	P. Density ($\mu W/cm^3$)
Arakawa [4]	0.4	10	0.4	6	-	-
Miao [5]	1.8	10	0.6	-	1.2	2
Saha [6]	0.5	2	12.7	300	-	-
Saha [6]	1	2.5	12.7	1860	-	-
Gen 1 [2]	1	10	3.68	558.3	**39.45**	**10.7**
Gen 2 [3]	1	10	2.12	288	**5.8**	**2.74**
*Functional volume of bench-top prototype						

Third Generation Piezoelectric PFIG Development

A third generation piezoelectric PFIG generator is being developed. This constitutes the first micro-scale piezoelectric generator reported capable of ≤10Hz operation. 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 by this Gen 3 device; by incorporating a brittle bulk piezoelectric ceramic (max. 1000μ strain) machined using ultrafast laser ablation. Additional benefits of transitioning to piezoelectric transduction include: reduced volume (halved), large rectifiable voltage, and the possibility of combining piezoelectric and electromagnetic transduction mechanisms. The fabricated device currently generates a peak power of 25.9μW and an average power of 1.21μW from an input acceleration of 9.8m/s2 at 10Hz. The device operates over a frequency range of 23Hz. The internal volume of the generator is 1.2cm3 (2.8cm3 including casing).

The spring suspension for the inertial mass is again made out of copper. The piezoelectric FIG is machined out of a PZT/Brass/PZT bimorph. The PZT layer is first ground down using a lapper, and Ti/Ni electrodes are evaporated and patterned. NdFeB magnets are adhered to the FIGs. This work also exceeds the power density reported by others. Efforts are underway to enhance this significantly by improving the fabrication mechanism and eliminating some unnecessary loss mechanisms.



(a) *(b)*

Figure 6. a) . Illustration describing the developed piezoelectric Gen 3 PFIG. b) Photograph of the assembled PFIG generator (left). A photograph of a single PZT spiral Frequency Increased Generator (FIG) photograph (right).

Conclusion

A novel inertial micro power scavenger architecture was developed in order to enable the effective scavenging of low-frequency non-periodic vibrations such as those appearing in the environment, human motion, and others. It utilizes the bi-stable motion of a mechanical mass to couple mechanical energy into one of two transducers, which convert it into electrical power. This project had as its aim to enhance the state-of-the-art in low-frequency, high-bandwidth vibration scavenging. This was achieved by implementing the PFIG generator architecture in three different micro power generators, each one enhancing certain aspects of the previous one, with the most recent version occupying a little over $1cm^3$, and opening the door to future integration.

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Patent Application

T. Galchev, H. Kim, and K. Najafi, "Non-Resonant Frequency Power Scavenger Architecture For Low-Frequency Ambient Vibration," Patent Pending. UM File #4362

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