

# Liquid-Rotor Electret Power Generator Array Energized by a MEMS-Based Pulsed Combustor

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## Abstract

A new Power MEMS system based on an aero-valved pulsed combustor and a Liquid-rotor Electret Power Generator (LEPG) is described here. The aero-valved pulsed combustor is a no-moving parts air-breathing engine that operates in single or cyclical pulses. The pulse combustor consists of an acoustic resonant chamber with an evaporator/spark chip, which consists of microfabricated fuel evaporation pads at the combustion zone and electroplated nickel spark electrodes. Single pulse and short duration resonant (~20 seconds) combustions have been achieved on a 3x scale combustor using gaseous reactants (propane/oxygen). The LEPG is a recently developed vibrational power generator [1,2]. The LEPG array described in this paper consists of 12 LEPGs with mercury droplets as the liquid-rotor. Preliminary power generation on the order of 100nWs has been achieved with valved compressed air while the target goal of the optimized array is on the order of 1mW.

**Keywords:** Pulsed Combustor, LEPG array, coupled efficiency

## 1. Introduction

In recent years, numerous concepts and designs of Power MEMS have been researched around the world [3]. The widely stated rationale for Power MEMS is to generate power for portable devices. This is not surprising at all given the orders of magnitude higher in energy density of hydrocarbon or other liquid fuels compared with the ubiquitous portable power source today, the battery. In terms of combustion-based Power MEMS, most devices demonstrated the use of either moving machineries (i.e., pistons and turbines) for mechanical energy extraction or no-moving parts combustor (catalytic combustion) for thermal energy extraction (i.e., thermoelectric generator). This paper presents a third approaching, using a no-moving parts combustion engine that allows mechanical energy extraction. The described system has two major benefits: 1) No moving parts at the hot section of the power generator system (the combustion zone), and 2) Utilizing mechanical energy extraction, which has demonstrated higher efficiencies, than thermal energy extraction methods [3].

## 2. Aero-Valved Pulsed Combustor

The aero-valved pulsed combustor proposed for this project is based on acoustic resonating combustor principles such as the Helmholtz or the Schmidt type combustors [4]. With the addition of an aerodynamic one way valve, evaporator pad, and integrated spark electrodes, our MEMS based pulsed combustor with no moving parts is realized. The pulse combustor starts by igniting the initial stagnant air and fuel mixture in the combustion chamber (Figure 1a) with the micro-patterned nickel plated spark electrode array controlled by direct IGBT-switching (Figure 1b). After the

start-up phase, the combustor will arrive at the designed resonating frequency which allows the spark electrodes to be turned off so no further externally supplied energy is required to sustain the combustor. In single pulse mode, the spark ignition will be needed for every pulse of the combustion. However, the single pulse mode allows long off times that may be more compatible with the vibrational mechanical-electrical converter. The fuel is then fed to the combustor through the micro fuel delivery channels via surface tension, and injected via the evaporative pad (Figure 1b). To shut down the combustor, the spark electrodes will ignite at off-phase to induce anti-resonance according to Rayleigh's criterion. In the single pulse mode, the combustor is simply ignited at sub-hertz frequencies to match the decay time of the spring coupler for power extraction by the LEPG. The key differentiating aspect of this MEMS combustor is that it is designed for self-aspiration with the ultimate goal of using liquid hydrocarbons (i.e., gasoline, JP8) without moving parts.

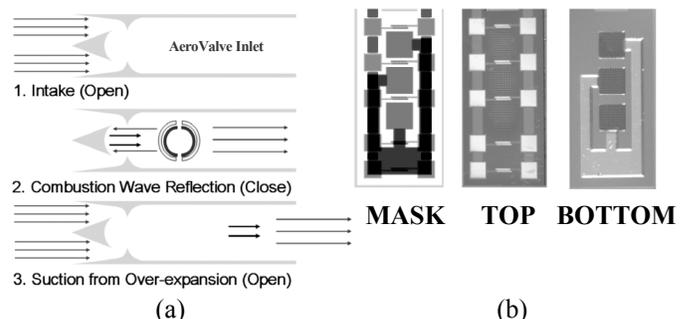


Figure 1. a) The simplified operational cycle of the aero-valved pulse combustor in resonance mode. b) The spark electrode and evaporator chip.

The fabrication steps for the spark electrode and the evaporator chip is shown on Figure 2. The fuel path to the evaporator is about  $\sim 50\mu\text{m}$  deep while the evaporator itself consists of  $\sim 400\mu\text{m}$  deep grooves with  $\sim 100\mu\text{m}$  hole diameters. The fuel paths leading to the evaporator are anodically bonded by Pyrex glass while the fuel port is CNC-drilled (500 $\mu\text{m}$  diameter).

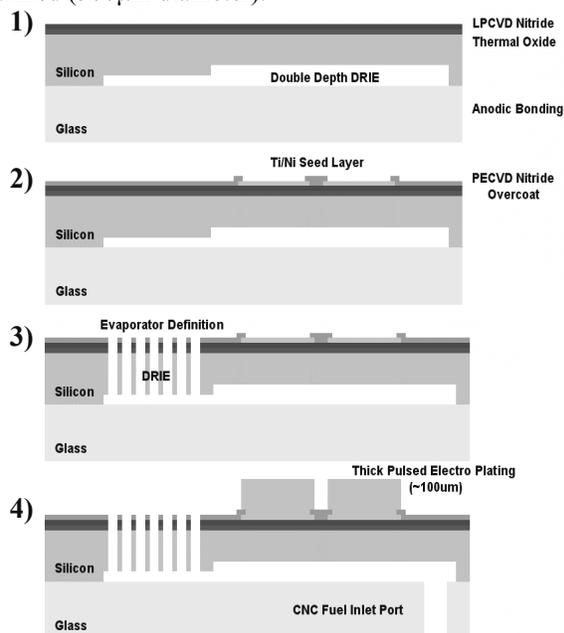


Figure 2. Fabrication process flow of the spark electrode and evaporator chip.

In order to permit rapid design iterations, the combustor body is CNC-machined alloy 6061 aluminum (Figure 3). The preliminary experiments for the combustor involve the single pulse ignition of the pulse combustor using solenoid-valved gaseous reactants (propane and oxygen). Interestingly, the combustor also achieved short duration self-resonating combustion ( $\sim 20$  seconds). However, the combustion intensity during resonance is orders of magnitude lower than single pulse mode. This most likely reflects the fact that the 3x scale combustor used is not optimized for such operations.



Figure 3. The spark electrode and evaporator chip in a  $\sim 3x$  scale combustor for single shot tests. The combustor tail section is 5cm long.

### 3. LIQUID-ROTOR ELECTRET POWER GENERATOR (LEPG)

The liquid-rotor electret power generator (LEPG) is designed to harvest electricity from mechanical vibrations. The device [1] consists of a fixed-charged, Teflon-electret capacitor with an air-filled channel acting as a gap and a liquid droplet that moves by vibration. The operational frequency and amplitude of the LEPG can be tuned by changing the channel geometries. As the liquid moves into and out of the gap, a net voltage is generated across the capacitor as image charges (induced by the electret) on the two electrodes redistribute according to the position of the droplet. The LEPG may be an economical method to harvest power from vibrational environments to power remote sensing devices. It has been shown that the generated power can be successfully increased by connecting LEPG devices in parallel or serial arrays [2].

### 4. EXPERIMENTAL SETUP

The LEPG array is utilized to couple the pulsed combustor via a spring system to match the jet exhaust of the combustor. Currently, a natural-vibrating system containing a LEPG array and a beam is used to measure the input displacement, the output power, and the efficiency of the LEPG for single pulse mode. The setup of the LEPG-spring efficiency testing is shown in Figure 4. A packaged LEPG array is attached to the free end of the cantilever beam with adjustable length. The array consists of 12 LEPG devices and the electret layer is implanted with  $2.1 \times 10^{-4} \text{ C/m}^2$  of surface charge. Each LEPG device consists of 2 pairs of electrodes. In all the tests reported here, only one pair is used to simplify the preliminary experimental setup. Each pair of the LEPG electrodes is also connected in parallel with other LEPGs on the array. With the exploitation of a micromanipulator, the end of the beam can be pulled and released. Its vibrating behavior can then be recorded by the capacitance change of two parallel aluminum pads.

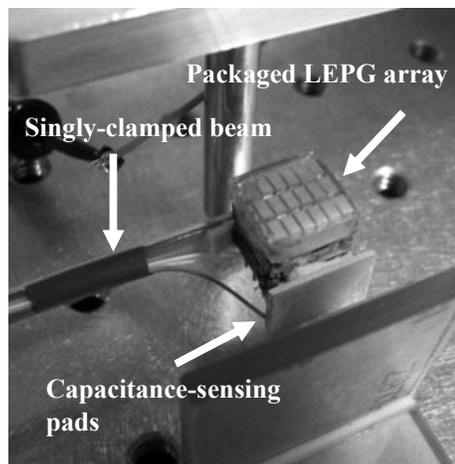


Figure 4. The LEPG-spring coupling measurement setup.

The displacement of LEPG-spring vibration is obtained from the converted voltage, which is implemented by a 0.342V/pF capacitance-sensing circuit based on Microsensors MS3110 IC. At the same time, the generated electrical power from the LEPG array is delivered to a 12.2MΩ load resistor, and the voltage across the resistor is extracted by a National Semiconductor LF356N op-amp used as a 10<sup>12</sup>Ω impedance voltage buffer. Both capacitive-sensing and output voltages are measured by a HP54645A digital oscilloscope and then exported to PC by a GPIB data acquisition kit.

**5. RESULTS AND ANALYSIS**

When a vibration-based power scavenging system is working, the output electrical energy is generated by an “additional” damping loss in the physical domain. The effect of it has been shown causing changes of the dynamic behavior in the system [4,5]. In the LEPG-spring coupling system, displacement waveforms of the LEPG array at 50Hz natural frequency, with and without load resistance, are shown in Figure 5. Since the channel length of LEPG devices is 2.5mm, displacement decayed from 1.25mm is used to analyze for the optimal droplet/wall collision inside channels instead of the ~7mm maximum peak-to-peak displacement in this experiment. Six cycles of vibration are counted for input/output power and efficiency analysis.

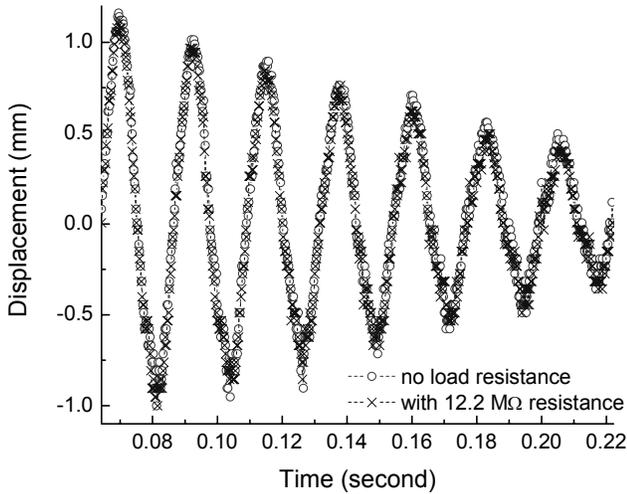


Figure 5. Natural vibration waveforms of the LEPG-spring system, with and without load resistance.

The waveform without load resistance shows the damping of viscous air drag, internal loss of the beam, and other dynamic mechanisms without any loss due to power extraction. With a 12.2MΩ load resistor, additional energy is removed from the system in the form of electrical energy, so the damping is increased and the corresponding waveform decays faster. The generated voltage across the load is illustrated in Figure 6. After taking the RMS value, the output electrical power is found to be 0.148μW.

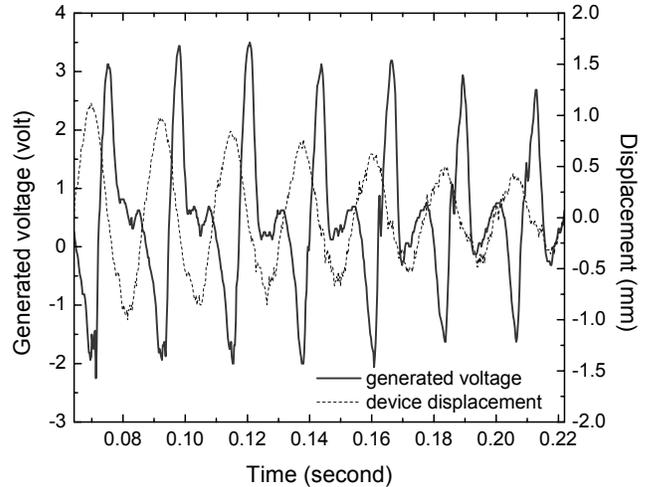


Figure 6. The waveforms of the damped displacement in the LEPG-spring system with 12.2MΩ load-resistor connection and the resulting output voltage.

For LEPG devices, the generated power can be dramatically improved through an optimized load matching and/or a multilayered LPEG stack. Figure 7 shows the continuous power output of the LEPG on a forced vibrating beam at 50Hz at 1.75mm peak-to-peak amplitudes. As the load resistance increases, so does the output power. This indicates that the maximum power output should actually be higher than at the maximum load resistance tested (30 MΩ). When the absolute maximum power is achieved, any further increase in load resistance will decrease the power generated since the peak voltage is achieved and can not go any higher.

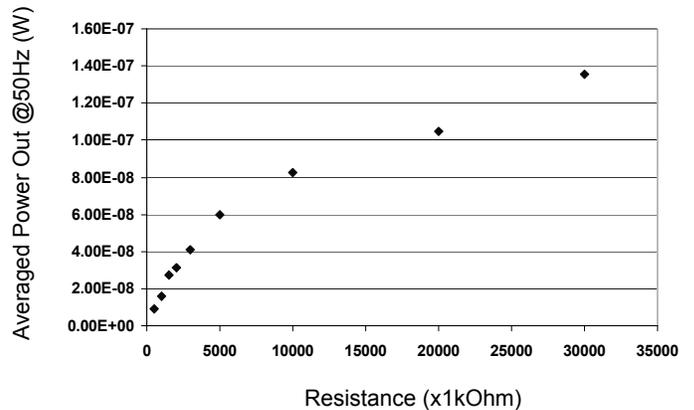


Figure 7. The time averaged power output as a function of load resistance with peak-peak vibration amplitude of 1.75mm.

The conversion efficiency of the LEPG devices is also expected to be a function of displacement and frequency. The relationships between them are needed to be characterized for the optimal performance. Internal losses such as contact friction, inelastic deformation of channel

walls, aerodynamic drag inside the channels and external losses such as viscous drag and spring loss of cantilever-mounted LEPG devices are also needed to be explored in greater detail.

## 6. CONCLUSION

The prototype 3x-scale pulsed combustor has been fabricated and tested in both single shot and resonant modes. Also, the coupled LEPG-spring system, using a cantilever beam, has been preliminarily tested. Under 50Hz natural vibration starting from 1.25mm displacement, the generated electrical power is 0.148 $\mu$ W. However, it should be noted that this power output is not optimized from the perspective of the optimum load resistance. Tests are currently ongoing with the goal of optimizing the LEPG before integrating with the pulsed combustor.

## ACKNOWLEDGEMENT

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