Technology Development for Self-Powered Sensors

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Abstract

This paper discusses the performance of an acoustic energy harvester employing an electromechanical Helmholtz resonator with a piezoelectric composite backplate. Sufficient energy is available in fluid/acoustic systems to potentially power elements of active flow control systems. Acoustic energy reclamation has been demonstrated using an electromechanical Helmholtz resonator excited by an incident acoustic field, successfully self-powering an electret microphone. The self-powered microphone calibration shows good agreement with a conventionally powered case. The proof-of-concept demonstration in this paper employed a linear regulator circuit to convert the ac piezoelectric generator voltage into a constant dc voltage.

1. Introduction

A typical active flow control system requires actuators, sensors, and, in the case of closed-loop control, a controller. Each of these key components requires power and must be linked via a communication system, typically entailing electrical wiring. This restricts the use of active flow control systems to environments that may be wired to a power grid. Depending on the actuation, sensing, and control schemes, such a distributed system is often complex and potentially expensive to implement. Control systems powered by batteries are not similarly constrained. The operating lifetime of a battery-powered system limits the system deployment time. An alternative approach, is to reclaim energy from available sources in the environment of the system and convert it into electrical energy to power the control system. In a fluid flow system, there are several available energy sources that can be harvested. For example, a turbulent flow over a wing or an acoustic pressure field in an engine nacelle possesses sufficient energy for self-powered sensors. Specifically, the acoustic intensity of a plane wave possessing a rms amplitude of 200 Pa is approximately 10 mW/cm². The development of a self-powered control system requires a transducer to convert available energy from the surrounding environment to useful electrical energy. This electromechanical transducer must be coupled to a self-booting power electronics module that rectifies and conditions the ac signal output of the transducer to create a stable dc voltage source.

In this paper, we report the performance of an acoustic energy harvester employing an electromechanical Helmholtz resonator with a piezoelectric composite backplate. Proof-of-concept data are presented in the form of a self-powered electret microphone calibration. The paper is organized as follows. First, a Helmholtz resonator with a compliant piezoelectric composite backplate is described. Next, a lumped equivalent circuit is presented for an acoustic energy generator. Converter circuits for extracting the power from the acoustic generator are then discussed. An overview is given of the experimental setup and representative data are presented for two cases. Specifically, the
acoustic calibration of a self-powered electret microphone is compared to the same microphone powered by a conventional dc power supply. Finally, the paper concludes with a summary and brief discussion of future work.

2. Background

In terms of technology development for self-powered flow control systems, potential energy sources that may be harvested include optical, thermal, mechanical, fluidic, and acoustic energy. The selection of the energy source depends on its availability and the power that can be extracted compared to the power requirements of the entire system. The size of the energy harvester/generator and its power scaling with size are additional considerations. The size may be classified as micro-scale, which are fabricated using microelectromechanical systems (MEMS) techniques, or meso-scale, which are fabricated using conventional machining technology.

Energy harvesting systems utilizing various energy sources have been developed possessing a range of size and power outputs. Solar energy was harvested from a 1 cm$^2$ array of microfabricated photovoltaic cells to produce an overall open circuit voltage of 150 V and short circuit current of 2.8 µA [1]. Thermal energy was extracted from a 0.75×0.9 cm$^2$ bismuth-telluride thermoelectric junction to produce 23.5 µW for a temperature difference of 20 K [2]. Meso-scale vibrational energy harvesting approaches include a moving coil generator (size not specified) that provided 400 µW when excited by a stochastic signal with a narrowband power spectral density centered at 2 Hz to simulate human walking [3]. A lead-zirconate-titanate (PZT) piezoelectric layer bonded to 7×9.5 cm$^2$ steel spring placed in the sole of a shoe generated a 2.2 mW output power by the force exerted during ambulatory motion [4]. Piezoelectric materials have also been used to damp mechanical vibrations by connecting passive electrical networks across the piezoelectric layer to dissipate the mechanical energy through an electrical resistor [5]. Single meso-scale piezoelectric cantilevers [6] and stacks [7] have been investigated for energy reclamation but were not operated in a stand-alone, self-powered mode. At the micro-scale, a MEMS variable capacitor has been designed and fabricated to harvest vibrational energy with a chip area of 1.5 × 1.5 cm$^2$ and a reported net power output of approximately 8 µW [8]. However, arrays of micro generators have not been optimized or even exploited. Power generation from fluidic energy has involved very large scale piezoelectric generators using ocean waves [9]. Recently, a meso-scale generator approximately 1 m long has been proposed for harvesting strain energy induced by the shedding of alternating vortices from a bluff body flow using a piezoelectric polymer [10]. In applications that require the deployment of sensors in an aeroacoustic environment, where optical, thermal, or vibrational energy is not readily available, acoustic energy harvesting represents a potential means for enabling self-powered sensors. This latter possibility is the subject of the current study.

3. Active Helmholtz Resonator

The acoustic energy reclamation device consists of a Helmholtz resonator with a compliant piezoelectric composite backplate coupled to an energy reclamation network as shown in Figure 1. Figure 1(a) shows a cross section of the resonator where $V$ is the cavity volume, $L$ and $S$ are the length and cross-sectional area of the neck, respectively, $P_i$ is the incident acoustic pressure, and $P_c$ is the cavity acoustic pressure. The top view is illustrated in Figure 1(b) with the radii of the neck and cavity as shown. The electromechanical actuator consists of an axisymmetric PZT patch bonded to a compliant metal diaphragm mounted to the resonator backplate. The composite diaphragm is driven into motion by the amplified cavity pressure at resonance. This motion in turn generates a strain field in the composite actuator, thus resulting in the generation of an ac voltage across the PZT patch.

4. Lumped Element Modeling

Lumped element modeling was used to analyze and predict the behavior of the compliant backplate Helmholtz resonator [11]. The lumped element system was then represented using an equivalent circuit model to facilitate the coupled simulation of the entire energy reclamation system. The equivalent circuit for this system is shown in Figure 2. In the notation below, the first subscript denotes the domain (e.g., “a” for acoustic), and the second subscript describes the element (e.g., “D” for diaphragm). Any subscripts that follow are descriptive of the lumped element.

A conventional Helmholtz resonator can be lumped into three idealized elements. The neck of the resonator constitutes a duct through which frictional losses are incurred and therefore possesses an acoustic resistance $R_{ac}$. In addition, the air that moves through the neck stores kinetic energy and
thus possesses a finite mass $M_{an}$. The neck impedance generally includes a nonlinear term associated with the orifice discharge and grazing flow effects. The compressible air in the cavity stores potential energy and is modeled as a compliance $C_{ac}$. In a conventional Helmholtz resonator, it is assumed that the walls of the cavity are perfectly rigid. For an electromechanical Helmholtz resonator, the compliant backplate displaces due to a differential applied pressure and thus possesses finite acoustic impedance [12, 13]. The strain field associated with this displacement in turn generates a charge on the piezoelectric electrodes. Up to the first resonant mode, the piezoelectric composite unimorph can be lumped into idealized discrete circuit elements using conjugate power variables. In this case, the differential pressure and voltage are effort variables, while current and volumetric flow rate are flow variables. Because an ideal piezoelectric unimorph is an indirect, conservative transducer, the electroacoustic transduction can be represented as a transformer with a parallel shunt blocked electrical capacitance, $C_{eb}$, attached to the electrical port and a series short-circuit acoustic compliance, $C_{ad}$, attached to the acoustic port as shown in Figure 2. The turns ratio of the electromechanical transformer is $\phi_\phi$. The acoustic mass and resistance of the compliant backplate diaphragm are $M_{ad}$ and $R_{ad}$, respectively. The details of the electromechanical model and parameter estimation can be found in Prasad et al. [14].

The structure of the equivalent circuit is explained as follows. An incident pressure $P_i$ drives a volume flow rate $Q_{in}$ through the orifice. The incident pressure fluctuation can be due to acoustic excitation and/or pressure fluctuations in a turbulent boundary layer over the resonator orifice. This volume flow rate through the orifice can either compress the fluid in the cavity or can displace the backplate. The backplate volume velocity is transformed to an electrical current that can either flow into the energy reclamation circuit or charge the piezoelectric capacitor. $C_{pzt}$, attached to the electrical port and a series short-circuit acoustic compliance, $C_{ad}$, attached to the acoustic port as shown in Figure 2. The turns ratio of the electromechanical transformer is $\phi_\phi$. The acoustic mass and resistance of the compliant backplate diaphragm are $M_{ad}$ and $R_{ad}$, respectively. The details of the electromechanical model and parameter estimation can be found in Prasad et al. [14].

\[ R_{L,PZT} = |Z_{th}| \quad \text{or} \quad R_{L,PZT} = \sqrt{R_{th}^2 + X_{th}^2}. \quad (1) \]

Since the Thévenin impedance for a piezoelectric generator is very high, on the order of several hundred kilo-ohms, a power converter is inserted between the acoustic piezoelectric generator and the electrical load to provide a high input impedance $R_{in}$ that approaches the $R_{in} = R_{L,PZT} = |Z_{th}|$ condition as illustrated in Figure 4.

The conversion of the time-varying ac voltage waveform into a dc voltage may be accomplished using a rectification stage and a linear regulator, a pulse-width modulated (PWM) switching converter, or a resonant converter [17]. Rectification followed by a peak detector and linear regulator is a simple method to convert the ac piezoelectric input waveform into a dc output voltage. However, the input impedance is a function of the output load impedance. Since the input impedance varies with load, power flow is not maximized. Furthermore, the linear regulator incurs dissipative losses. Switching converters transfer energy by switching a low-loss
inductor across a storage capacitor and exhibit high efficiencies in excess of 80%, depending on the peak voltages, switching frequency, and component parasitic characteristics. The control signal for the switching transistor is a PWM signal. The power required to generate the PWM signal must be considered in stand-alone switching converters. Resonant converters employ the electrical resonance between the converter inductance and the generator capacitance to efficiently transfer energy from the generator to the converter. Switches commutate to transfer energy stored in the inductor to the storage capacitance.

For proof-of-concept of the feasibility of acoustic energy reclamation to self-power a sensor, we employ the simple linear regulator circuit shown in Figure 5 [4]. As discussed previously, the input impedance of the linear regulator is a function of the output impedance. The linear regulator is designed to connect the storage capacitor via a switch to the linear regulator and output impedance after the threshold value. Thus, the output impedance does not load the piezoelectric generator during the majority of the power transfer cycle.

The first stage of the linear regulator circuit consists of a full-wave rectifier bridge (D1-D4) which inverts the negative waveforms of the generator output. The piezoelectric generator may be viewed as a current source that charges the storage capacitor, C1. Initially, the piezoelectric output is connected only across C1 and a voltage sense circuit consisting of transistors Q1 and Q2 and Zener diode, D5. The voltage sense circuit is designed to trigger when the voltage across C1 exceeds the sum of the Zener diode voltage to approximately 5 V and the forward emitter-base voltage drop of the P/N/P bipolar junction transistor, Q3, or approximately 12.6 V. When this trigger voltage is exceeded, transistor Q1 conducts and a voltage is applied between the gate and source terminals of the diode-protected n-channel metal-oxide-semiconductor field-effect transistor (MOSFET), Q2, exceeding its threshold voltage. Q2 then turns on, closing the circuit for the storage capacitor C1 to discharge through the micropower regulator circuit (Maxim 666). The micropower regulator circuit delivers a stable 5 V dc output as long as the input voltage to the regulator IC is greater than approximately 5 V. Therefore, as the storage capacitor, C1, discharges from 12.6 V to 5 V, the power converter circuit provides a regulated 5 V dc voltage to the load, enabling the operation of a sensor or electronics designed for a 5 V bias. If the low battery detect circuit is enabled, when the input voltage to the regulator circuit falls below 5 V or other specified low battery input threshold, a low battery output (LBO) signal on the circuit falls from 5 V to ground. The negative falling edge generates a negative pulse through the capacitor C3. This negative pulse cuts off transistor Q1, which turns off the pull-up of the gate voltage of transistor Q2, disconnecting the storage capacitor, C1, from the regulator chip. Then, the entire cycle repeats as the piezoelectric generator charges the isolated storage capacitor, C1. If the disconnect of C1 is disabled, then when C1 discharges below 4.5 V, the output of the regulator circuit follows the voltage of C1.

Thus, the linear regulator circuit exhibits three types of behavior depending on whether the power dissipation at the load is greater than the power input from the generator and whether the low battery interrupt is enabled. If the rate of energy dissipation at the load at 5 V is greater than the energy input to the storage capacitor, then the output of the linear regulator circuit is 5 V only while the voltage across C1 is greater than approximately 5 V. With the low battery interrupt enabled, the output of the switched regulator will produce a periodic 5 V output while C1 discharges from 12.6 V to approximately 5 V and then the output storage capacitor is discharged to zero while C1 recharges back to 12.6 V. With no low battery interrupt enabled, the output of the switched regulator will sag below 5 V and reach a steady-state value until a power balance is achieved. On the other hand, if the rate of power dissipation with the load at 5 V is less than the energy input from the generator, then the output of the switched regulator will remain at 5 V regardless of whether the low battery interrupt is enabled.

6. Experimental Setup

The purpose of the experiments described is to demonstrate a proof-of-concept of the feasibility of acoustic energy reclamation to self-power a sensor. The sensor employed is an electret microphone. Experiments were conducted in the Interdisciplinary Microsystems Laboratory at the University of Florida. As shown in Figure 6, two different plane-wave tubes were used in the setup. Grazing-incidence plane waves were generated in a 8.5 mm x 8.5 mm square duct with a pere - termination to provide acoustic excitation for the piezoceramic-backplate Helmholtz resonator. Normal-incidence plane waves were generated in a second 25.4 mm x 25.4 mm square duct to calibrate a self-powered electret microphone vs. a reference microphone.

The resonator cavity consists of a 12.7 mm diameter, 19.05 mm deep cylindrical hole. The resonator neck is a 4.76 mm diameter, 3.175 mm deep cylindrical hole. All parts of the Helmholtz resonator and the two plane wave tubes were
machined from aluminum and sealed using neoprene gaskets and vacuum grease. To monitor the cavity pressure, a Brüel & Kjaer (B&K) type 4138 microphone was mounted flush with the cavity wall. The incident sound pressure level (SPL) was measured by mounting another B&K type 4138 microphone flush with the duct wall immediately opposite of the resonator neck. The incident SPL and frequency of the plane waves in the grazing-incidence tube were both varied. In these experiments, the frequency was adjusted to correspond to the first resonance frequency of the coupled resonator [12], while the incident SPL was adjusted to provide a suitable voltage level from the piezoceramic to power the electret microphone.

The piezoceramic composite backplate was a PZT unimorph bender element from American Piezo Corp that consists of a 0.18 mm thick brass disk bonded to a thin PZT disk. The brass disk was clamped between two aluminum plates with 25.4 mm diameter holes and attached to the backside of the cavity. The diameter of the compliant back plate was made larger than that of the cavity by milling out a small recess near the clamping point. This was designed to provide an improved impedance match between the cavity and diaphragm compliances.

The electrical leads of the piezoceramic disk were connected to the input of the linear regulator energy reclamation circuit. The output of the circuit provided power to an electret microphone (Panasonic energy reclamation circuit. The output of the circuit were connected to the input of the linear regulator compliances.

This was designed to provide an improved impedance match between the cavity and diaphragm compliances.

The microphones and various electrical voltages in the energy reclamation circuit were connected to a B&K PULSE Multi-Analyzer System Type 3560. The PULSE system served as the power supply and data acquisition unit for the microphones and also generated the source waveforms for the compression drivers. The calibration waveform consisted of a periodic random signal that was band-limited between 1 and 7.4 kHz , while a sinusoid was used to excite the active Helmholtz resonator. These signals were fed through Techtron 7540 amplifiers to JBL Pro 2426H compression drivers. The spectral measurements were obtained using 6400 bins from 1 to 7.4 kHz , yielding a frequency resolution of 1 Hz with 1000 averages. Data below 1 kHz were discarded, as there was no source excitation below 1 kHz due to driver limitations. The data above the cut-on frequency of the calibration tube were also discarded due to contamination from higher-order modes.

7. Results and Discussion

Prior to the self-powered sensor demonstration, the dependence of the PZT output voltage of the electromechanical Helmholtz resonator was investigated. The 8.5 mm square duct grazing incidence plane wave tube was driven at a resonance frequency (2.18 kHz) of the resonator for varying incident SPL with an open circuit across the PZT layer. As the incident SPL and hence cavity SPL was increased, the open circuit voltage increased commensurately. For the open circuit condition, the PZT voltage was sinusoidal at the excitation frequency.

The output of the PZT was then connected to the linear regulator. Since one electrode of the PZT was grounded through the aluminum resonator, the PZT output voltage was isolated using a 1:1 isolation transformer. The isolated PZT output voltage was then connected to the input of the linear regulator circuit shown in Figure 5, and the electret microphone connected at the output of the linear regulator through a 2.2 kΩ load resistor to bias the field-effect transistor buffer amplifier. The output of the electret was ac coupled through a 10 nF Mylar capacitor and sampled. A number of test voltages and currents were measured simultaneously at the PZT, within the linear regulator circuit, at the output of the linear regulator circuit, and across the bias resistor of the electret microphone.

As discussed in Section 5, the switched linear regulator circuit connects only the storage capacitor across the piezoelectric generator while the capacitor voltage is less than the threshold voltage of the Zener diode and the forward bias of Q1, approximately 13-15 V. Figure 7 plots the voltage and current at the output of the PZT for 145 dB SPL measured in the cavity where the peak PZT voltage is approximately 15V. The output of the linear regulator is 0 V. When the cavity SPL is increased to 157 dB, the increased PZT voltage triggers the threshold detect circuit, connecting the linear regulator and electret load to the storage capacitor. This additional loading of the PZT distorts the PZT voltage and current waveforms as shown in Figure 8. The output of the linear regulator circuit is 5 V and was used to acoustically self-power the electret sensor for the calibration measurements. The output of the linear regulator circuit was stable at 157 dB cavity pressure, indicating that the power dissipation at the load was less than the power input from the piezoelectric generator.

The electret was calibrated using a reference B&K Type 4138 condenser microphone for two cases: (1) self-powered using the 5 V output of the acoustic energy reclamation device and power
converter and (2) conventional 5 V dc power supply biased electret. The magnitude of the calibration for the two cases is shown in Figure 9, and the phase is shown in Figure 10. Good agreement is observed for the self-powered electret calibration compared to the dc power supply case, demonstrating an acoustically self-powered sensor.

The power flow was estimated using laser displacement measurements of the diaphragm and the measured cavity pressure, the measured voltages and currents from the PZT, and the voltage to the electret load. The available power levels are tabulated in Table 1. The estimated power conversion efficiency is 11% from the diaphragm motion to the PZT and 37% for the power conversion from the PZT to the electret load. The low power efficiency is a consequence of the simple topology of the linear regulator and can be improved with more complex converter schemes.

Table 1: Summary of available power estimates

<table>
<thead>
<tr>
<th>Diaphragm motion</th>
<th>( Q_{\text{Diaphragm rms}} )</th>
<th>( P_{\text{Cavity rms}} )</th>
<th>180 mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric transduction</td>
<td>( \frac{1}{T} \int_{t_{1}}^{t_{2}} I_{\text{PZT}}(t) V_{\text{PZT}}(t) dt )</td>
<td>20 mW</td>
<td></td>
</tr>
<tr>
<td>Electrical load</td>
<td>( V_{\text{load}}^{2}/R_{\text{load}} )</td>
<td>7.4 mW</td>
<td></td>
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</tbody>
</table>

8. Conclusions and Future Work

Sufficient energy is available in fluid/acoustic systems to power elements of active flow control systems. Acoustic energy reclamation has been demonstrated using an electromechanical Helmholtz resonator excited by an incident acoustic field, successfully self-powering an electret microphone. The self-powered microphone calibration shows good agreement with a conventionally powered case. The proof-of-concept demonstration in this paper employed a linear regulator circuit to convert the ac piezoelectric generator voltage into a constant dc voltage. Further work includes development of a self-powered switched converter based on a discontinuous conduction mode fly back converter described elsewhere [18, 19] to provide a matched resistive input impedance independent of the output load and also a resonant converter. The incident pressure will also be characterized further by considering the effects of the scattering due to the Helmholtz resonator [20].

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References


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Figure 1: Diagram showing a cross sectional view (a) and top view (b) of a Helmholtz resonator with a compliant composite piezoelectric backplate.

Figure 2: Equivalent circuit representation of an electromechanical Helmholtz resonator.
Figure 3: Thévenin equivalent circuit.

Figure 4: Thévenin equivalent for piezoelectric generator connected to the input of a power converter. The output of the power converter is connected to a load such as a sensor.

Figure 5: Linear regulator circuit for piezoelectric power conversion [4].

Figure 6: Schematic of impedance tube terminated by compliant-backplate Helmholtz resonator.
Figure 7: Time series data of $V_{pzt}$, $I_{pzt}$ for a cavity SPL of 145 dB. Output of power converter = 0 V.

Figure 8: Time series data of $V_{pzt}$, $I_{pzt}$ at cavity SPL of 157 dB. Output of power converter = 5 V.

Figure 9: Comparison of magnitude versus frequency for self-powered electret (excitation conditions: 157 dB cavity pressure, power converter 5 V output) and conventional 5 V biased electret. Sensitivity calibration made with respect to B&K type 4138 condenser microphone.

Figure 10: Comparison of phase versus frequency for self-powered electret (excitation conditions: 157 dB cavity pressure, power converter 5 V output) and conventional 5 V biased electret. Sensitivity calibration made with respect to B&K type 4138 condenser microphone.