Transduction as energy conversion; harvesting of acoustic energy in hydraulic systems

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Energy harvesting from acoustic energy sources is a form of transduction. While energy densities in typical airborne acoustic noise fields are extremely low, those in hydraulic systems may be orders of magnitude greater and represent an opportunity for direct energy conversion from piezoelectric materials for powering sensor and communication nodes. Hydraulic systems are challenging from a design perspective in that the device must be capable of withstanding static pressures up to and exceeding 35 MPa, while being simultaneously exposed to dynamic pressures on the order of 3.5 MPa. Hydraulic pressure energy harvester devices have been developed to exploit the high energy densities of dynamic pressures in hydraulic systems. There is an immediate application for this technology in that state-of-the-art hydraulic hose and piping systems employ integral sensor nodes for structural health monitoring for early detection of incipient failures. This paper presents the acoustic and electromechanical modeling of the piezoelectric power output from dynamic pressure in terms of the force transmitted into an energy harvester designed for hydraulic systems.
INTRODUCTION

The “harvesting” of ambient energy sources for powering sensing and communications electronics has been widely researched over the last decade\textsuperscript{1,4}, with the ambient energy sources including light, wind, flow, vibrations, and acoustics. The main goal has been to enable a variety of self-powered wireless electronic systems. Motivations for the work have been elimination of maintenance required to replace batteries, elimination of the chemical waste associated with conventional batteries, elimination of wiring, enabling the installation of sensors in remote or difficult to access areas, etc. A large body of the prior research in this area has focused on the conversion of vibrations into electricity\textsuperscript{2}. A much smaller body of work addresses the conversion of fluid-borne acoustic energy into electricity. The common devices for energy conversion employ a piezoelectric beam or membrane, an electroactive polymer, or an inductive coil and magnet arrangement. The focus of the paper at hand is energy harvesting from acoustic disturbances, as such, the remainder of this review will address this literature.

A fundamental challenge of harvesting energy from acoustic noise is the very low energy density that is typically available. For example, in air, a 60 dB plane wave has an intensity of approximately 1 \( \mu \text{W/m}^2 \), a 100 dB plane wave intensity is 10 mW/m\textsuperscript{2}, and the intensity of a 140 dB plane wave is approximately 100 W/m\textsuperscript{2}. These sound fields correspond to a conversational level, an uncomfortable loud level which would cause hearing damage from continuous exposure (and a temporary shift in hearing threshold for shorter exposures) and a level beyond the threshold of pain. If one seeks to harvest energy from a typical low level acoustic signal in the environment, either one must have a large device (or efficient focusing), or have a need for only very low power levels. In pumped fluids, however, the situation is somewhat different, as the use of positive displacement pumps can lead to significant intensities within fluid systems\textsuperscript{5}, with intensities on the order of kW/m\textsuperscript{2} possible.

Taylor et al.\textsuperscript{6} developed an electromechanical acoustic energy harvester based on a Helmholtz Resonator as a means for increasing the pressure amplitude from an acoustic field. This development, as well as those of Liu et al.\textsuperscript{7} and Phipps et al.\textsuperscript{8} considered the electromechanical Helmholtz Resonator energy harvester for use as an element within a self-powered active control method for noise within the nacelle of a jet aircraft engine. One wall of the Helmholtz Resonator was a circular piezoceramic plate, such that the pressure response of the resonator would drive the piezoceramic and thereby permit electrical energy extraction. Phipps asserted that the sound field within engine nacelles could approach 160 dB, an intense airborne field. In a related development of the concept, Horowitz et al.\textsuperscript{9} considered a MEMS; it must be pointed out that the energy harvesting results reported did not include a resonator. A key point to make about this approach, though, is that the power output of a Helmholtz Resonator-based energy harvester is still limited by the incident intensity of the acoustic wave field; a Helmholtz Resonator acts as a concentrator and effectively increases the “size” of the device, but it can’t extract more energy than is actually present.

Addressing the low intensity of typical airborne acoustic wavefields, Wu et al.\textsuperscript{10} used a periodic array of rods to create a “sonic crystal” to focus incident sound into a cavity within the sonic crystal. They placed a PVDF membrane inside the cavity and were able to generate a peak output of approximately 35 nano-watts from a 7 Pa pressure difference across the membrane (it is unclear if this is the acoustic pressure, if so, it corresponds to a 111 dB sound field in the cavity; the incident sound field on the sonic crystal was not specified).

Lallert et al.\textsuperscript{11} considered a means to increase the energy harvesting efficiency from an acoustic source through a nonlinear harvesting circuit. The device used a circular PZT disk on a baffled flexible metallic membrane exposed to an incident wave field. The device generated up to 55 \( \mu \text{W} \) for excitation at resonance with an imposed 100 dB sound pressure level. The surface area of the membrane was 78.54 cm\textsuperscript{2}, such that the surface power density of the device was 0.7 \( \mu \text{W/cm}^2 \).

A related class of work uses an acoustic response as an intermediate energy conversion process. For example, Kim et al.\textsuperscript{12} developed on energy harvester using a Helmholtz resonator excited by a mean flow with electromagnetic transduction. Stevens implanted a thermoacoustic engine driven by the temperature difference between ambient air and ground; electrical conversion was handled using the thermoelectric effect. Hernandez et al.\textsuperscript{13} used flow instability to excite a tonal response of a pipe; a piezoelectric element was used for electrical energy production.

In this paper, the exploitation of pressure fluctuations in hydraulic systems is investigated for low power electricity generation through piezoelectric transduction. An energy harvesting technology might be integrated with health-monitoring sensors in a hydraulic system\textsuperscript{14} and eliminate the need for batteries or wires. A particular advantage of energy harvesting in fluid hydraulic system is that the pressure disturbance is often periodic in nature, such that the bulk of the energy is carried by one or a limited set of frequency components; this is in contrast to the
majority of energy harvesting sources considered to date, where the energy distribution tends to be broadband and random. Another aspect unique to fluid hydraulic system is that they can be subject to high static pressures, e.g. 35 MPa, combined with acoustic pressures on the order of 5 to 10% of the static pressures. The fluid hydraulics community uses the terms “pressure ripple” and “dynamic” pressure for acoustic pressure. The high pressure and fluid nature of the system argue against the use of unbacked diaphragms, wafers, or films such as have been used in other energy harvesting applications.

In the following, a Hydraulic Pressure Energy Harvester (HPEH) prototype is introduced for converting pressure ripple into electricity by using a piezoelectric stack arrangement. Details of the testing procedure and performance results are presented for various static and dynamic pressure levels. A lumped-parameter electromechanical model is also described and validated to predict the electrical power output in terms of the hydraulic pressure ripple.

**MODELING**

The following briefly explores the energy or intensity available for harvesting in an acoustic field, and then presents the modeling of the power generation from a device designed to extract energy from acoustic waves in a fluid system.

**Available Acoustic Energy in a One-dimensional Waveguide**

The focus of the work in this paper is on wave propagating in fluid piping systems, with emphasis on plane traveling waves. While many of the papers that speak generically to potential sources of energy for harvesting cite acoustics as an opportunity, few of them actually consider the available energy in an acoustic field. The intensity of an acoustic plane wave is

\[
I = \frac{P_{\text{rms}}^2}{\rho c}
\]

where \(P_{\text{rms}}\) is the root-mean-square pressure, \(\rho\) is the density, and \(c\) is the speed of sound. Table 1 provides the intensity for airborne waves at 100 dB and 160 dB re 20 \(\mu\)Pa sound pressure levels, and for 220 and 240 dB re 1 \(\mu\)Pa in hydraulic fluid. Intensities are provided in terms of W/m\(^2\), as well as mW/cm\(^2\); the latter scaling is provided since milliwatt level power from centimeter-scale devices is desired for common energy harvesting applications. The 160 dB level in air was chosen for consideration in Table 1 as it corresponds to the level cited by Phipps et al.\(^8\) as possibly present within aircraft engine nacelles. The 100 dB in air level was chosen as it is a noise level that one may find in a noisy industrial process. The two fluid hydraulic examples were chosen as they reflect what may be measured in pumped hydraulic systems. As noted in the Introduction, it is not uncommon that the acoustic pressure to be ~10% of the static pressure of the system. As such, the 220 dB re 1 \(\mu\)Pa level represents a low pressure system (~2.8 MPa static pressure) while the 240 dB level represents a high pressure system (~28 MPa). The main point to appreciate from Table 1 is that the acoustic intensity within pumped, pressurized fluid systems can be very high, orders of magnitude higher than the intensity that is present in typical acoustic noise fields, and in many instances will be even higher than what might found in quite intense airborne sound fields (e.g., the field in an engine nacelle as considered by Phipps et al.\(^8\)).

<table>
<thead>
<tr>
<th>Wave field</th>
<th>Pressure, rms, kPa</th>
<th>Intensity, W/m(^2)</th>
<th>Intensity, mW/cm(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air, 100 dB re 20 (\mu)Pa</td>
<td>0.002</td>
<td>0.01</td>
<td>0.001</td>
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<tr>
<td>Air, 160 dB re 20 (\mu)Pa</td>
<td>2.0</td>
<td>9,640</td>
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<tr>
<td>Hydraulic fluid, 220 dB re 1 (\mu)Pa</td>
<td>100</td>
<td>8,210</td>
<td>821</td>
</tr>
<tr>
<td>Hydraulic fluid, 240 dB re 1 (\mu)Pa</td>
<td>1,000</td>
<td>821,000</td>
<td>82,100</td>
</tr>
</tbody>
</table>

**Power Generation from a Hydraulic Pressure Energy Harvester**

Figure 1 depicts the key elements of a Hydraulic Pressure Energy Harvester (HPEH) mounted on a fluid hydraulic system. The housing of the HPEH retains a multilayer piezoelectric stack, and has a connection to the fluid system. The stack is exposed to pressure forces in the fluid system through an interface that serves to isolate
the stack from the fluid, while permitting pressure forces to be coupled into the stack. The stack has a cross-sectional area $A_{\text{stack}}$ while the interface has area $A_{\text{interface}}$; these areas need not be equal, and indeed, if $A_{\text{interface}} > A_{\text{stack}}$, greater force would be coupled into the stack than if the stack alone was exposed to the system pressure. The effective area of the HPEH may be represented as $A_{\text{eff}} = \gamma A_{\text{stack}}$, where $\gamma$ is typically greater than unity.

**FIGURE 1.** Simplified schematic of hydraulic pressure energy harvester, where the interface implements fluid-mechanical coupling between the piezoelectric stack and pressure ripple in a pressurized fluid with pressure ripple present.

Consider an HPEH using a multi-layer stack as its active element, terminated with a resistive load as depicted in Figure 2a (more sophisticated energy harvesting circuits are available in the literature, but are not considered here as such are not essential to the focus of this paper). An electrical equivalent model is depicted in Figure 2b, where the stack is represented as a current source in parallel with a capacitance. Each layer within the stack has a piezoelectric $d_{33}$ coefficient assumed to be the same for each layer, and capacitance $C_{p}^i$ also assumed to be the same for each layer. If the stack has $N$ active layers in parallel, all subjected to the same force $F$, then the effective $d_{33}$ and capacitance of the entire stack may be expressed as

$$d_{33}^{\text{eff}} = N d_{33}^i \quad \text{and} \quad C_{p}^{\text{eff}} = N C_{p}^i .$$

**FIGURE 2.** a) Multi-layer stack terminated with a resistive load impedance and subject to an applied pressure force, b) Equivalent electrical circuit with the stack modeled as a current source in parallel with a capacitance.

Assuming bulk values for the capacitance and $d_{33}$ then leads to

$$C_{p}^i = \frac{d_{33}^i A_{\text{stack}}}{h} \quad (2)$$

where $A$ is the cross-sectional area of each layer, and $h$ is the thickness of each layer. The response equation for the energy harvest circuit is then

$$C_{p}^{\text{eff}} \ddot{v} + \frac{1}{R_l} \dot{v} = d_{33}^{\text{eff}} \dot{F} \quad (3)$$

where $\dot{v}$ is the induced voltage. Let the disturbance (force) input be represented as a harmonic function,

$$F(t, \omega) = F_0 e^{i\omega t} . \quad (4)$$

Therefore, the voltage response will also be a harmonic function

$$v(t, \omega) = V_0 e^{i\omega t} . \quad (5)$$
Upon substitution of Eqs. (4) and (5) into Eq. (2) and solving for the ratio between the force input and voltage response (the voltage frequency response function), one obtains

\[ \alpha(\omega) = \frac{V_0}{F_0} = \frac{\omega d_{33}^{\text{eff}}}{\omega C_p^{\text{eff}} + R_i}. \]  

(6)

The power output is then

\[ \Pi = \left| \frac{\omega d_{33}^{\text{eff}}}{\omega C_p^{\text{eff}} + R_i} \right|^2 \left( \frac{\omega d_{33}^{\text{eff}} F_0}{1 + (\omega R_i C_p^{\text{eff}})^2} \right)^2. \]  

(7)

The maximum power output is obtained for the load resistance that maximizes Eq. (7), which is found by setting

\[ \frac{\partial \Pi}{\partial R_i} = 0. \]  

(8)

This yields the optimal load resistance for maximum power as

\[ R_i^{\text{opt}} = \frac{1}{\omega C_p^{\text{eff}}}. \]  

(9)

With this optimal load resistance, the maximum power output is then

\[ \Pi_{\text{max}} = \Pi|_{R_i = R_i^{\text{opt}}} = \frac{\omega (d_{33}^{\text{eff}} F_0)^2}{2 C_p^{\text{eff}}}. \]  

(10)

or

\[ \Pi_{\text{max}} = \frac{\omega N h d_{33}^{\text{eff}} F_0^2}{2 e_{33}^{\text{eff}} A_{\text{stack}}}. \]  

(11)

With the applied force amplitude equal to the applied pressure times the effective area, or \( F_0 = P_0 A_{\text{eff}} \), then

\[ \Pi_{\text{max}} = \frac{\omega N h d_{33}^{\text{eff}} (P_0 A_{\text{eff}})^2}{2 e_{33}^{\text{eff}} A_{\text{stack}}} = \frac{\omega N h d_{33}^{\text{eff}} P_0^2}{2 e_{33}^{\text{eff}}}, \]  

(12)

where \( V \) is the volume of the active layers of the stack.

**PROTOTYPE**

A prototype HPEH device was built using a multilayer piezoelectric PZT stack of dimension 6.8 mm by 6.8 mm and a length of 30 mm. The measured effective piezoelectric strain coefficient for the stack was 182.93±0.56 nC/N. The measured capacitance of the stack varied between 3.06 \( \mu \)F and 3.11 \( \mu \)F, dependent on the static pressure imposed on the stack. The optimal load resistance for maximum power generation predicted by Eq. (9), given these physical parameters for the stack, is 114\( \Omega \). The device was designed to withstand a static pressure of 34.5 MPa (5000 psi).

**FIGURE 3.** HPEH prototype with threaded connector for attachment to fluid hydraulic system.
RESULTS

Testing of the HPEH prototype device was performed on hydraulic flow rig, schematically depicted in Figure 4a, that employed a nine-piston pump operating at 1500 rpm, yielding a fundamental pressure ripple frequency of 225 Hz. The needle valve in the rig was used for setting the static pressure. The HPEH was installed on a mounting block within the rig; the mounting block permitted exposure of the HPEH to the pressure fluctuations within the hydraulic fluid, and included a dynamic pressure sensor enabling calibrated measurements of the pressure fluctuations. The data acquisition system is schematically represented in Figure 4, where the decade resistance box was used to set and vary the resistive load impedance applied to the HPEH.

Example time traces of the dynamic pressure in the mounting block and the corresponding voltage produced by the HPEH are presented in Figure 5. The voltage produced is closely matched to the pressure waveform, indicating effective coupling to the pressure input as well as effective conversion. The spectral content of the input pressure and the response voltage is depicted in Figure 6. The bulk of the acoustic energy in the pressure ripple is in the second harmonic of the pump passing frequency, at 450 Hz.

![Figure 4](image1.png)

**FIGURE 4.** Testing configuration for phase 3, including the sensor and the data acquisition system.

![Figure 5](image2.png)

**FIGURE 5.** Dynamic pressure (upper plot, psi and kPa) measured at position of HPEH, and corresponding stack voltage (lower plot), static pressure 3.45 MPa (500 psi), load resistance 120Ω.
The measured and modeled power produced by the HPEH for a range of load resistances at static pressure setpoints of 2.07 and 3.45 MPa (300 and 500 psi) on the test rig is depicted in Figure 7. Note that the static pressure is not significant for the power conversion operation of the HPEH, rather, the pump produces different magnitude of pressure ripple at different static pressure setpoints. The data in Figure 7 reflects consideration of the total actual pressure in the pressure input, as well as just the pressure at 450 Hz where the bulk of the acoustic energy is present. The peak power is produced for a load resistance around 120Ω, which corresponds to the optimal load resistance predicted by Eq. (9); because of the flat slope of the power versus resistance response data, it is not possible to precisely identify the optimal resistance from Figure 7. However, this flat response also implies a relative insensitivity to error in setting the load resistance for maximum power. Also of significance in Figure 7 is that the power produced by the HPEH at the 3.45 MPa (500 psi) setpoint exceeds 1 mW; this is well above the power requirement reflected in the literature for wireless sensing nodes. And, the 3.45 MPa setpoint is low for hydraulic systems, which commonly operate in the 20 to 35 MPa range and higher, and would have correspondingly greater pressure ripple.

![Figure 6](image)

**FIGURE 6.** Spectrum of measured pressure and HPEH response voltage, static pressure 3.45 MPA (500 psi), load resistance 120Ω.

![Figure 7](image)

**Figure 7.** Comparison of the total power generated and the power generated at the peak harmonic of 450 Hz at static pressures of 2.07 MPa and 3.45 MPa; the 2.07 MPa setpoint yielded an average $P_{\text{rms}}$ of 58.1 kPa, while the 3.45 MPa setpoint yielded an average $P_{\text{rms}}$ of 109.2 kPa.
CONCLUSIONS

Direct conversion of the energy carried by the dynamic pressure within a fluid hydraulic system has been demonstrated to be feasible and viable as a source for energy harvesting applicable to wireless self-powered sensing and communication. The high static pressure and dynamic pressure of hydraulic systems argues for the use of direct off-resonance conversion instead of on-resonance as has been the focus of most other energy harvesting approaches. Milliwatt-level power was produced by a prototype device at relatively low operating pressures for a hydraulic system. The power produced is viable for typical wireless sensing applications.

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REFERENCES