Investigation on Electromagnetic Vibration Energy Harvesting in Water Distribution Control Valves

Victor Ordoñez, Robert Arcos, Jordi Romeu, and Andreas Josefsson

Abstract—Control stations of a water distribution system monitor several variables such as the pressure, the flow, and the quality of water. For these monitoring tasks, wireless sensor networks with ultra-low power consumption powered by vibration-based energy harvesters as an alternative to the usage of batteries or wired connections might be a suitable option in these facilities. This article investigates the potential applicability of an electromagnetic vibration energy harvester prototype in different control valves of a water distribution system in the province of Barcelona by means of experimental measurements and numerical simulations. The low-amplitude vibration with random excitation is measured with piezoelectric accelerometers in three control valves under normal operating conditions to process each signal and determine the dominant frequency in the complete spectrum, which is found to be in the order of magnitude of kHz, and the dominant frequency in the range of 10 to 100 Hz, where commercial harvesters normally operate. Numerical simulations of the harvester prototype are conducted in all cases with the same materials, geometries, and coil parameters, generating a maximum RMS load voltage and output power when the harvester's natural frequency matches the dominant frequencies of each vibration signal. The maximum output power estimated in these simulations is 1573.04 nW with a corresponding RMS load voltage of 53.6 mV and optimal load resistance of 1830 Ω.

Index Terms—Control valves, electromagnetic harvester, electromagnetic vibration energy harvesting, vibration-based harvester, water distribution system.

I. INTRODUCTION

In the last decades, the development and usage growth of ultra-low-power devices, microelectromechanical systems (MEMS), Internet of Things (IoT), and wireless sensor networks (WSNs) have been driving investigation on different techniques for energy harvesting (EH) from the environment to replace batteries or wired connections as power sources for operation [1], [2]. On the one hand, batteries present several problems such as current leakage and restricted lifespan, which brings up to inevitable periodical replacement with hazardous disposal, an increase in labor cost [3], and the addition of new disturbances to already burdened maintenance and logistical personnel [4]. On the other hand, wired energy connections face difficulties of their own such as the cost of installation and limited displacement for portable devices [1], [5]. Therefore, the use of WSNs for different monitoring purposes offers several advantages, one of the most significant being that wireless systems can provide continuous, periodical or one-time monitoring without the associated installation costs of wiring [6], which depending upon the infrastructure and size of the sensor network can reach up to 80% of the total cost of installation [7].

Mechanical vibration is the most common type of mechanical energy for harvesting. It is ubiquitous in built and natural environments and is not affected by radio wave, solar or thermal conditions. Manmade sources of mechanical energy (e.g., machinery, infrastructures, and transportation) can emit high levels of harmonic vibrations or low levels of random vibrations, these last ones being challenging to harvest efficiently. Moreover, natural mechanical energy is usually related to vibrations induced by wind or water flow [8]. EH from wind and water are well-developed and worldwide implemented technologies as alternative sources for large-scale electrical production. However, harvesting energy from these sources is a relatively new investigation field when sustaining low-power applications as WSNs [6].

Many researchers [9]-[12] have begun to consider flow-induced vibration energy harvesting (VEH) due to steady and unsteady states of fluid flows, also because of instability phenomena such as turbulence, galloping, flutter, and vortex. These types of energy harvesters may provide advantages compared to traditional turbines that harvest kinetic energy from the wind, steam, or water because they can be inefficient for some locations, too expensive, and their overall efficiency is affected because of mechanical losses at the bearings when miniaturizing [6]. For instance, Zhou et al. [13] investigated a novel type of piezoelectric tubular energy harvester based on fluctuating fluid pressure. Numerical simulations were conducted to investigate the influence of the geometrical parameters, the input mechanical load parameters, and the output electrical load parameters upon the output performance of the proposed device with a maximum output power of 0.23 W. Hsieh et al. [14] studied a micro heat pipe harvester
based on a piezoelectric vibration-induced power device. The deformation of the piezoelectric material by means of steam impact enables it to convert the mechanical energy into electrical energy with a maximum output voltage of 535 mV. Shukla et al. [15] evaluated the energy harvesting potential from the flow-induced vibrations of a real-size water pipeline, which includes multiple bends, T-joints, and valves. Several piezoelectric films were mounted on the surface of the pipeline with different configurations and locations to simultaneously collect vibration-induced energy data. The results obtained from these experimental tests reveal a maximum output RMS voltage of 700 mV.

Control valves are a critical part of any fluid flow control circuit. Therefore, they are used in different industries to regulate the flow working variables according to different requirements and necessities. It is known that vibration of high amplitude can occur when the valve is suddenly closed, producing a water hammer effect in the system where the upstream pressure increases considerably due to inertia while the pressure wave propagates through the fluid [16]. Also, due to the cavitation formed by excessive differential pressure in the liquid which leads to the erosion of its elements, higher noise, and a decrease of its life service [17], [18]. Contrarily, the operation of a control valve under normal conditions can generate a lower vibration amplitude due to the fluid flow circulating through a variable obstacle. The complete understanding of these flow-induced vibration signals is still under study, given the complexity of the vibration generation mechanisms and a large number of variables that affect it, for example, the type of flow, the pressure, the speed, and the density of the fluid, as well as the mechanical and geometrical properties of the pipe-valve system.

The aim of this study is to investigate the potential applicability of an electromagnetic vibration energy harvester (EMVEH) prototype in water distribution control valves by means of experimental measurements and numerical simulations. Control stations monitor several variables of a water distribution system such as the pressure, the flow, and the quality of water. Hence, WSNs with ultra-low power consumption [19] might be powered by an EMVEH as an alternative to the usage of batteries or wired connections in these facilities.

II. THEORETICAL BACKGROUND

Regardless of the configuration or architecture, an EMVEH is always composed of a mechanical subsystem integrated by a mass-spring-damper and an electromagnetic subsystem formed by a coil-magnet. The basic analytical theory of both subsystems is commonly known and it is applied to understand the influence of the most relevant input parameters on the electrical output performance. However, the analytical theory has barely been implicated in the design process where random vibrations, magnetic flux leakage, inner displacement limits, and magnetic field calculations must also be taken into consideration [20].

A. Mechanical subsystem

The design of an EMVEH is mainly based on the frequency content and the amplitude of vibration of the host system where the harvester will be applied. The device will provide maximum output power when its natural frequency matches the frequencies (excitation frequency from now on) where most of the spectral energy of the host system vibration is located. If the excitation frequency deviates from the harvester’s natural frequency, the performance of the harvester will drastically reduce. However, in most practical cases, the excitation frequencies present in a particular direction and location on the host system may not be well known or may vary over a certain range [21]. A vibration-based generator was first analyzed and documented by Williams and Yates [22] as a linear single degree of freedom mechanical model with external base excitation. It consists of a mass \( m \) attached to a spring with stiffness \( k \), and a damping element with viscous damping coefficient \( c \), as illustrated in Fig. 1.

![Fig. 1. General model of a resonant vibration transducer with base excitation.](image_url)

In this image, the transducer’s housing displacement of vibration is represented by \( y = y(t) \), whereas the relative motion of the mass with respect to the housing by \( z = z(t) \). Considering the global damping as \( c = (c_m + c_e) \), where \( c_m \) is the mechanical damping and \( c_e \) is the electrical damping (attributed among others to eddy currents, heat in the spring, friction, and the electrical resistance), the governing equation of motion of the system is:

\[
m\ddot{z} + (c_m + c_e)\dot{z} + kz = -m\ddot{y}.
\]

(1)

For further analysis, we assume that the mass of the vibration source is much greater than the mass \( m \) of the resonant vibration transducer so it remains unaffected by the movement of the generator. Thus, the corresponding transfer function associated to (1) in the frequency domain can be written as [20]-[22]

\[
H_{XY}(\omega) = \frac{\omega^2}{\omega_n^2 - \omega^2 + 2i(\zeta_n + \zeta_e)\omega\omega_n},
\]

(2)

where \( X \) and \( Y \) are the displacements of vibration \( x \) and \( y \) in the frequency domain, respectively, \( \omega_n^2 = k/m \) is the natural angular frequency of the undamped oscillation, \( \omega \) is the angular frequency, and \( \zeta_n + \zeta_e = (c_m + c_e)/(2m\omega_n) \) is the normalized damping factor.
B. Electromagnetic subsystem

The model for the electromagnetic subsystem is based on Faraday's law of electromagnetic induction. An EMVEH transforms vibrations or kinetic energy into electricity by moving a coil across the magnetic field of a stationary magnet or, inversely, by moving the magnetic field of a magnet across a stationary coil [23]-[25]. This results, in both cases, on the induction of an electromotive force $\varepsilon$ through the conductive coil, expressed as [26]

$$
\varepsilon = -\frac{d\Phi}{dt} = -\left(\frac{dA}{dt} B + \frac{dB}{dt} A\right),
$$

where $A$ is the area of the coil’s surface, $B$ is the magnetic flux density, and $\Phi$ is the magnetic flux linkage, which can also be expressed in terms of the relative velocity between the coil and the magnet as

$$
\frac{d\Phi}{dt} = \frac{d\Phi}{dz} \frac{dz}{dt} = k_i \dot{z},
$$

in which $k_i$ is the transduction factor and it can be approximated as a constant. For the harvester’s electric circuit presented in Fig. 2, the expression of load voltage $V_l$ neglecting the coil inductance $L_c$ can be estimated as

$$
V_l = \frac{R_l \varepsilon}{R_l + R_c},
$$

where $R_c$ and $R_l$ is the coil and load resistance of the circuit, respectively. Then, the output power of an EMVEH device can be expressed as given by (6). It is clear from these equations that harvested power is mainly governed by the load resistance, the magnetic flux linkage, the coil resistance, and the relative motion of the coil and the magnet [20], [26]-[29].

$$
P_{out} = \frac{V_l^2}{R_l}.
$$

C. Coupled electromechanical system

For the simulation of the harvester performance, models of the mechanical and electromagnetic subsystems are coupled in a global model that is related via the transduction factor $k_i$. Fig. 3 shows a simplified flowchart of the model, which results in the load voltage and output power of the EMVEH due to some particular vibration conditions of the host system. However, the following considerations must also be applied to maximize the output power [22], [30]:

- The natural frequency of the device should match the excitation frequency of the host system.
- The damping factor should be designed to be small enough to maximize mass displacement.
- The moving mass should be as large as possible.
- Reduced resistance of the coil so that it is an order of magnitude smaller than the load resistance.
- Unwanted damping and stray losses should be as small as possible.

![Fig. 3. Simplified flowchart of the output power calculation procedure.](image)

III. METHODS

A. Experimental setup

Experimental tests are carried out at the control stations of a water distribution system in the province of Barcelona. In total, three control stations meet the minimum required conditions to measure the vibration levels on the control valves, which are: the pressure gauges and flow meters work optimally, pressure and flow data are monitored and saved in real-time, and there is a significant pressure difference before and after the valve. Fig. 4 illustrates the basic diagram of a typical water distribution control station whereas Table I presents the technical parameters of each station.
To perform the vibration measurements, an accelerometer connected to the data acquisition system is wax-fixed to the top surface of each valve as seen in Fig. 5. A required sampling frequency of 11000 Hz is determined after several initial tests by analyzing the maximum dominant frequencies of each spectrum. Once the sampling frequency has been established, measurements are made for 20 hours on each of the selected control valves under normal operating conditions of the water distribution system, detecting no relevant variations in the vibration signals. Hence, only a range of 240 seconds of each measured signal is used for this study.

### TABLE I

**TECHNICAL PARAMETERS OF THE SELECTED WATER DISTRIBUTION CONTROL STATIONS**

<table>
<thead>
<tr>
<th>Valve</th>
<th>Diameter (mm)</th>
<th>Pressure difference (kg/cm²)</th>
<th>Flow (m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control station 1</td>
<td>V1</td>
<td>100</td>
<td>2.24</td>
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<tr>
<td>Control station 2</td>
<td>V2</td>
<td>150</td>
<td>2.54</td>
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<tr>
<td>Control station 3</td>
<td>V3</td>
<td>200</td>
<td>2.55</td>
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</table>

### B. Transducers and data acquisition system

PCB Piezotronics seismic accelerometers (393A03) with a frequency range of 0.2 to 6000 Hz and sensitivity of (± 5%) 1000 mV/g are employed for all measurements. For the sake of reliability, each accelerometer is calibrated with an IMI 699A02 handheld shaker. Signals measured with the accelerometers are recorded with an autonomous acquisition system of the company Tentacle Gmbh.

### C. Signal processing

The signals acquired at each valve are observed in Fig. 6 and processed in MATLAB software to obtain the power spectral density (PSD) as illustrated in Figs. 7 and 8. It is clear from these images that V1 has a higher energy content than V2 and V3, and that dominant frequencies are different for each one, but still in the range of kHz. Thus, the numerical simulations of the EMVEH and each vibration signal will be conducted under two different resonance frequencies, which are: the dominant high-frequency $f_h$ in the complete spectrum and the dominant low-frequency $f_l$ in the range of 10 to 100 Hz (commercial device). Table II presents the most relevant vibration parameters for each signal, in which the RMS is the root mean square of the full range vibration signal.

### TABLE II

**VIBRATION PARAMETERS OF MEASURED SIGNALS**

<table>
<thead>
<tr>
<th>Valve</th>
<th>RMS (g)</th>
<th>$f_h$ (Hz)</th>
<th>$f_l$ (Hz)</th>
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<tr>
<td>V1</td>
<td>0.0351</td>
<td>2324</td>
<td>64</td>
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<tr>
<td>V2</td>
<td>0.0313</td>
<td>3779</td>
<td>89</td>
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<tr>
<td>V3</td>
<td>0.0194</td>
<td>1408</td>
<td>54</td>
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Fig. 6. Time domain signals of the vibration at all 3 control valves.

![Fig. 7. PSD of all 3 vibration signals for the full range of frequencies.](image-url)
Fig. 8. PSD of all 3 vibration signals in a range of 10 to 100 Hz.

D. Numerical simulation

The numerical model of an EMVEH prototype developed at ReVibe Energy Company with FEMM, Matlab & Simulink commercial software has been applied in order to estimate the RMS load voltage and output power generated with each signal at different load resistance and two natural frequencies, \( f_0 \) and \( f_i \). On the one hand, FEMM is a program for solving electromagnetic problems on 2D planar and axisymmetric domains. It has been used to estimate the system’s magnetic flux linkage \( \Phi \) as a function of the mass displacement based on the geometrical boundaries, materials properties and coil parameters, exposed among others in Table III. An example of this simulation is presented in Fig. 9, in which it can be observed that the maximum flux concentration occurs in the middle region of the back, and also that there is negligible leakage flux outside the boundaries of this element. On the other hand, Matlab & Simulink have been used to calculate the above-mentioned coil parameters, the relative motion of \( z \), the transduction factor \( K_T \) as a function of the mass displacement illustrated in Fig. 10 (together with the magnetic flux linkage), the electromotive force \( \varepsilon \), and the output values of the EMVEH performance.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Copper</th>
<th>NdFeB 32</th>
<th>Brass</th>
<th>1010 steel</th>
<th>3600</th>
<th>5130</th>
<th>3600</th>
<th>69.7</th>
<th>31.2</th>
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<th>198</th>
<th>121</th>
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It is clear from these images that maximum output power of 154.14, 41.33, and 1.22 nW occur at 1830 Ω with a corresponding RMS load voltage of 16.8, 8.7, and 1.5 mV for V1, V2, and V3, respectively. Figs. 13, 14, and 15 illustrate the output power at optimal load resistance against different natural frequencies from 59 to 69 Hz, 84 to 94 Hz, and 49 to 59 Hz for V1, V2, and V3, respectively. As one expected, the maximum output power occurs when the natural frequency of the device matches the $f_n$.

**B. High-frequency EMVEH**

For the next simulations, the dominant high-frequency $f_h$ of the vibration at V1, V2, and V3 is applied as the harvester’s natural frequency. Figs. 16 and 17 present the RMS load voltage and output power of the high-frequency EMVEH at different load resistance, respectively. Maximum output power occurs also at 1830 Ω due to the fact that no other parameter than the natural frequency of the device has been modified.
Figs. 18, 19, and 20 illustrate the output power at optimal load resistance as a function of the harvester’s natural frequency. The estimated RMS load voltage of the vibration at V1, V2, and V3 is 53.6, 38.5, and 31.3 mV, and the output power is 1573.04, 811.42, and 536.38 nW, respectively. Table IV presents a comparison of the simulated output performance of the low-frequency and high-frequency EMVEH and the power conversion efficiency $\eta$ of the device calculated according to [31]. The RMS exposed in Table IV represents the root mean square of the vibration signal filtered in a range of $\pm 10$ Hz of the natural frequency.

**Fig. 18.** Output power as a function of the EMVEH natural frequency for V1.

**Fig. 19.** Output power as a function of the EMVEH natural frequency for V2.

**Fig. 20.** Output power as a function of the EMVEH natural frequency for V3.

---

**TABLE IV**

<table>
<thead>
<tr>
<th>COMPARISON OF THE OUTPUT PERFORMANCE OF THE LOW-FREQUENCY AND HIGH-FREQUENCY EMVEH SIMULATIONS</th>
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<tbody>
<tr>
<td>Low-frequency EMVEH</td>
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<td>Valve</td>
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<tr>
<th>High-frequency EMVEH</th>
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<td>Valve</td>
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<td>V2</td>
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Power conversion efficiency $\eta$: 62%

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**V. CONCLUSIONS**

The above-mentioned results present a general idea of the potential applicability of an EMVEH prototype in three control valves (V1, V2, and V3) analyzed in this article by means of experimental measurements and numerical methods, leading to the following conclusions: The vibration generated at V1, V2, and V3 is found to be low-amplitude signals of random nature where the spectral energy is not concentrated in a single frequency but distributed along the range of 0 to 5500 Hz. Thus, the non-harmonic conditions and the low-amplitude vibration signals at the valves make the vibration harvesting a challenging task. The low-frequency and high-frequency EMVEH simulations will generate maximum output power when its natural frequency matches the dominant high-frequency $f_h$ and the dominant low-frequency $f_l$, respectively, at optimal load resistance of 1830 $\Omega$. The output power estimated with $f_h$ is 10.2, 19.6, and 439.6 times higher than the calculated with $f_l$ for V1, V2, and V3, respectively. Future work will consider the optimization of different materials properties, coil parameters and experimental validation with the EMVEH prototype.

**ACKNOWLEDGMENT**

Authors would like to express their deep appreciation to SOREA and ReVibe ENERGY companies for approving the use of *in situ* vibration measurements and research collaboration in the field of electromagnetic vibration energy harvesting, respectively.

**REFERENCES**


