Towards Self-Powered Devices Via Pressure Fluctuation Energy Harvesters

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Abstract

The growing interest in the Internet of Things has created a need for wireless sensing systems for industrial and consumer applications. In hydraulic systems, a widely used method of power transmission in industry, wireless condition monitoring can lead to reduced maintenance costs and increase the capacity for sensor deployment. A major problem with the adoption of wireless sensors is the battery dependence of current technologies. Energy harvesting from pressure fluctuations in hydraulic systems can serve as an alternative power supply and enable self-powered devices. Energy harvesting from pressure fluctuations in the process of converting small pressure fluctuations in hydraulic fluid into a regulated energy supply to power low power electronics. Previous studies have shown the feasibility of pressure fluctuation harvesting. However, for the development of self-powered sensor systems, the methods and techniques for converting pressure fluctuations into electrical energy should be further investigated.

This thesis explores the methods, limitations, opportunities, and trade-offs involved in the development of pressure fluctuation energy harvesters in the context of self-powered wireless devices. The focus is on exploring and characterizing the various mechanisms required to convert pressure fluctuations into electrical energy. In this work, an energy harvesting device consisting of a fluid-to-mechanical interface, an acoustic resonator, a piezoelectric stack, and an interface circuit is evaluated. Simulations and experimental analysis were used to investigate these different components for excitations relevant to hydraulic motors.

The results of this work provide new insights into the development of power supplies for self-powered sensors for hydraulic systems using pressure fluctuation energy harvesters. It is shown that with the introduction of the space coiling resonator for pressure fluctuation amplification and a detailed analysis of the fluid interface and power conditioning circuits, the understanding of the design and optimization of efficient pressure fluctuation energy harvesters is further advanced.
Sammanfattning


Processen för att utvinna av energi från tryckfluktuationer sker genom omvandling av små tryckfluktuationer i hydraulvärtska till elektrisk energi som strömförsörjer lägeffektelektronik. Tidigare studier har visat att det är möjligt att energiskörda från tryckfluktuationer.

För att kunna utveckla sensorsystem som är självförsörjande på energi så bör metoder och tekniker för att omvandla tryckfluktuationer i hydraulsystem till elektrisk energi undersökas ytterligare.

Denna avhandling undersöker metoderna, teknikerna och avvägningarna som är involverade i utvecklingen av tryckfluktuationens energiskördare i samband med självdrivna enheter. Fokus ligger på att utforska och karakterisera de olika omvandlingsmekanismerna som krävs för att omvandla tryckvågor till elektrisk energi.

I detta arbete undersöks en energiskördare som består av ett gränssnitt till hydraulsystemet, en akustisk resonator, en piezoelektrisk stack samt elektriska kretsar.

Simuleringar och experimentell analys har används för att undersöka begränsningarna, avvägningarna och optimeringsmöjligheterna för de olika systemen som utgör energiskördaren. Särskild uppmärksamhet har ägnats åt applikationers tryckfluktuationer har låg frekvens och amplitud excitation. Detta arbete ger ny inblick i utvecklingen av strömförsörjning för självdrivna sensorer för hydrauliska system som använder tryckfluktuationens energiskördare. Resultaten visar att införandet av nya strukturer för energifokusering och förstärkning av tryckvågor, liksom den detaljerade analysen av mekaniska gränssnitt och kretsar för effektkonditionering, ger ytterligare information för utformningen och optimeringen av energiskördaren.
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’Tis but a scratch!
Acknowledgments

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“Yesterday the day got colder
Passed away got one day older
Now it seems that everything is new”

Dr. Dog
Introduction

In hydraulic systems, harvesting energy from pressure fluctuations can enable the development of self-powered sensors. Ultimately, this eliminates the need for batteries, improves flexibility and scalability of sensor deployment, and reduces maintenance costs.

Self-powered systems are those that operate by harnessing the ambient available energy in the context of the system. In practice, self-powered system works by converting just enough energy from the environment to maintain operation; the main purpose is to operate without external electrical power.

A wireless self-powered sensor in its most minimal configuration consists of a sensing element, an energy harvesting device, and an electronic system with wireless capabilities.

Self-powered sensors for hydraulic systems can facilitate the use of multiple condition monitoring devices, which are becoming increasingly common in commercial and industrial applications. Condition monitoring brings several benefits, such as prevention of failures, which reduces system downtime and maintenance costs. Thus playing an important role in the development of the Industrial Internet of Things.

In this work, the different methods and technological solutions to convert pressure fluctuation into electrical energy that can be used by low power electronic devices are studied and evaluated. The main objective is to highlight the design considerations, performance, limitations and opportunities that arise in the development of pressure fluctuation energy harvesters as the sole power supply for electronics. This section explains the motivation, problem formulation, research challenges, and scope of the study. Section II provides a summary of the research papers included in this comprehensive summary, explaining the key contributions, limitations and how they relate to the identified challenges and research questions. Section III discusses the theoretical background required to describe the principles and highlight the challenges of energy harvesting through pressure fluctuations. Section IV discusses the main results and key findings of the research and highlights the implications of the main contributions as well as the limitations. Section V summarizes the
challenges of the research and discusses the proposed solutions in the context of the future of pressure fluctuation energy harvesters.

1.1 Internet of Things and Energy Harvesting

Industry is experiencing a digital transformation that aims to leverage the Internet of Things (IoT) to increase efficiency and become more agile. A growing number of studies and market research report huge gains for industries that adopt wireless technologies to improve their processes.\[1\]-\[3].

The industrial IoT represents a world where any thing can communicate with people, the Internet, and other things. In the context of industrial environments, these things include sensors that can provide information about the status of a machine. Imagine a future where bearings, bolts, flanges, pipes, i.e. every part of a machine can provide information about the state of the system. The benefits of constant monitoring would not only improve error prevention, but also enable better control of processes.

However, the implementation of industrial IoT is met with difficulties. One of the many challenges to the success of industrial IoT is powering the many things. First of all, wireless devices cannot rely on wired infrastructures to function. Therefore, they rely on batteries.

Several studies discuss the role of batteries in the future of IoT, namely extending battery life and developing green alternatives.\[4\]. This is because the finite life and negative environmental impact of current battery technologies are shortcomings that will become increasingly important as more devices are developed for the IoT. For example, battery replacement can make device maintenance expensive and dangerous, such as replacing the battery for every device on a factory floor and in hazardous environments.

For this reason, researchers have proposed energy harvesting (EH) as a more sustainable technology for powering the IoT. Energy Harvesting is the process of collecting energy from the environment and converting it into electrical energy. Figure 1.1 shows a conceptual representation of a general energy harvesting system example. To enable energy self-powered systems, energy harvesting systems must efficiently convert ambient energy into a regulated electrical power supply that can meet the operational requirements of an embedded system with wireless capabilities.

There is no single technical solution for energy harvesting; each potential application must be evaluated to find viable energy sources. In addition, implementation of the solution requires careful adaptation to each environment. Consequently, there is a need to understand the technologies and methods that can harvest the most energy. In general, EH does not intend to generate large amounts of electrical energy. The main goal is to generate enough energy to power wireless sensors and devices. Despite advances in reducing the energy consumption of modern embedded systems and wireless transmitters,
Figure 1.1: Conceptual representation of an energy harvesting system serving as a power supply.

energy harvesting technologies should convert energy as efficient as possible, taking into consideration the constraints of the application.

In general, the main conditions for the feasibility of EH in any environment are the following:

- Suitable environmental source for harvesting, where the ambient energy exceeds the amount required for a wireless system.
- Adequate harvester conversion performance, where the harvester technology and power extraction electronics can convert a sufficient amount of energy. The performance of the energy harvester would be constrained by size and cost, as well the impact on the host.

The implementation of reliable EH represents a leap from traditional systems that use batteries and wired connections. However, there are still some challenges to overcome before widespread deployment.

1.2 Self-Powered Wireless Sensors for Hydraulic Systems

Hydraulic systems are one of the most popular systems in industrial and consumer applications. These systems use pressurized fluid to transmit power and perform work. Whether in mining, offshore facilities, construction, or transportation, hydraulic systems offer high capacity, high strength, compactness, and efficiency. The need for condition monitoring of hydraulic systems has been widely discussed in recent years [4–6]. Compared to other power transmission systems, hydraulic machines do not require electrical power, except for the pump and some other elements such as valves. A wired electrical infrastructure or battery-dependent devices only increase the cost and maintenance of the system. For example, pressure changes in a hydraulic machine often occur before failure occurs [7]. If the condition of the machine is known, preventive maintenance can be performed instead of corrective action. In terms
of practicality, a self-powered device can transmit sensor data wirelessly. This eliminates the need for visual inspections, which can be dangerous for personnel. In addition, various hydraulic machines require monitoring of operating variables, whether for control or fault prevention. For example, hydraulic motors require flow, temperature, pressure and rotation measurements, among others. Therefore, the battery-dependent sensor can cause problems when the battery is exhausted and needs to be replaced. Maintenance on the motor can force a production shutdown, disassembly of the motor, and possible hazardous scenarios for personnel. If long-lived energy harvesters can be developed, then deployment and maintenance problems could be addressed. In addition, readings from the motor’s energy harvester-enabled wireless sensors can be received by a central calculation unit on the main system pump.

To enable self-powered devices in hydraulic systems, an energy harvesting device should be able to harness energy from the hydraulic system environment during operation. The amount of available energy and the efficiency of the conversion mechanisms define the feasibility of energy self-powered operation.

Within the different types of ambient energy in hydraulic systems, pressure fluctuation is one of the promising alternatives to enable energy self-powered devices. This was first discussed by Cunefare et al. in [8]. The authors discussed the potential of harvesting energy from pressure fluctuations, an ambient energy commonly identified as noise associated with system operation.

There are different types of noise in hydraulic systems, namely fluid-borne, structural-borne, and airborne noise. The noise originates at the pump (and other moving elements) and propagates through the fluid. Typically, the amplitude of pressure fluctuations in current hydraulic systems is up to 10% of the static pressure [8]. The frequency of fluctuations is a function of pump characteristics and operating speed. Common values for the frequency of pressure fluctuations are in the range of 10 Hz to 1000 Hz. The energy level associated with acoustic energy in hydraulic systems makes them practical for energy harvesting [8], [9]. However, the characteristics of the hydraulic system impose several mechanical constraints that limit energy conversion.

There are many reports on Pressure Fluctuation Energy Harvesters (PFEHs) for different environments. Ren et al. [10] proposed an electromagnetic PFEH for pressure fluctuations in gas. The harvesters converted the pressure fluctuations into the motion of a magnet inside a cavity. The authors measured AC power of 2.01 mW for a pressure variation of about 0.4 bar at 20 Hz for a system with a static pressure of 1 bar [10]. Other types of PFEH have been constructed with membranes that deform in response to pressure variations and convert the stress into electrical energy via piezoelectric patches. Mo et al. [11] demonstrated this principle and evaluated the thickness and diameter requirements of the diaphragm, emphasizing the negative influence of static pressure and the maximum deformation of the plate
before rupture. Wang et al. [12] demonstrated a PFEH that transforms pressure fluctuations generated by a Karman vortex street. The authors reported AC power of 0.7 nW for a pressure fluctuation of about 0.003 bar at 52 Hz. The prototype was evaluated at very low pressure values. Another type of electromagnetic PFEH for water systems was reported in [13], where the authors demonstrated an energy harvester for a system with pressure fluctuations of 0.0025 bar at 30 Hz, which showed AC power of 0.4 mW at low output voltage (5.5 mV). Cao et al. [14] proposed a PFEH for water distribution systems with low static pressure, their prototype consisted of an amplified multilayer piezoelectric stack with a resonant frequency around 100 Hz. The proposed energy harvester produced an open-circuit voltage of 83.6 mV for a pressure variation of 0.09 bar at about 93 Hz and a static pressure of 2.5 bar. Although there is an obvious interest in pressure fluctuation in different environments, research on PFEH for high static pressure environments (e.g., hydraulic systems) is limited to the studies in [8], [15–20].

![Figure 1.2: General representation of a Pressure Fluctuation Energy Harvester introduced in 8.](image)

Cunefare et al. proposed a PFEH for for hydraulic systems in [8], [9]. Figure 1.2 shows the general architecture of the PFEH presented in [8], which consists of a piezoelectric stack protected by a flat metal plate that serves as an interface with the fluid. This configuration of PFEH allows for high static compression strength while still harvesting energy form small pressure variations. In general terms, the process of the PFEH to convert acoustic energy into electrical power is as follows:

1. A interface exposed to the fluid that converts the dynamic pressure into a mechanical force.
2. A transducer that converts the force into electrical power.
3. An interface circuit that rectifies, regulates, and manages the time-varying energy generated by the transducer.

The amount of energy in pressure fluctuations that the PFEH can convert to electrical energy depends on the output of the various elements that convert
acoustic energy into a regulated electrical DC power source. In recent years, researchers have developed and investigated various structures and techniques to achieve this. The research efforts found in the literature are categorized below according to their role in converting acoustic energy into electrical energy. These categories are as follows: (a) fluid-to-mechanical interface and acoustic resonators, which study the conversion of pressure fluctuations into a mechanical force; (b) energy converters, which involves devices that transform mechanical energy into electrical energy; (c) interface circuits, which process and manage the electrical energy so that it can be used by an electronic device.

**Fluid-to-mechanical Interface and Acoustic Resonator**

The studies concerning the fluid-to-mechanical interface are limited to the work of Cunefare et al. [8], Skow et al. [15], [16].

Cunefare et al. [8] presented a study detailing the transduction of pressure fluctuations using a piezoelectric device matched to a resistive load. This work is mainly exploratory and proposes the basic structure and methods for PFEH. The experimental study is limited to an evaluation considering a commercial pump, resulting in pressure fluctuations at 225 Hz with 450 Hz and 900 Hz harmonics and a fixed static pressure.

Skow et al. [16] extended the research in [8] by investigating PFEH in high pressure scenarios. The authors developed a spring mechanism to reduce the static force acting on piezoelectric stacks under high pressure.

The results of this work suggest that a flat metallic interface combined with a metallic spacer can transfer acoustic energy into mechanical force. However, the authors do not report on the behavior of the fluid-mechanical interface across frequencies. Instead, the authors introduce the concept of an empirical effective interface, which includes the efficiency of the fluid-to-mechanical interface, assuming that it is constant across pressure and frequency.

In practice, pressure amplitude is translated into force at the fluid-mechanism interface. This leads to the case where an interface with a larger exposed area provides more force and therefore more power. However, as the exposed area increases, the static load on the plate also increases, which can compromise the integrity of the interface. Although compliant systems, e.g., backplates [21]–[24], resonant diaphragms [11], or resonant piezoelectric [14], which can be used to support both the active material (i.e., also contain the energy transducer) and the fluid-to-mechanical interface, can have higher performance in terms of the power generated and the small volume of the device, they are not an ideal solution for hydraulic systems. This is because the static pressure can lead to the mechanical failure of the system, similar to the increase of the area of the fluid-to-mechanical interface.

To enhance power without increasing the interface area researchers have introduced acoustic resonators such as the Helmholtz Resonator. The resonator is an acoustic device that can increase the amplitude of pressure fluctuations
at a certain frequency. Helmholtz resonators are commonly used in hydraulic systems to reduce unwanted noise in the fluid (i.e., they absorb and amplify pressure fluctuations within the cavity of the device) \[25-30\].

The authors in \[15, 18\] propose the use of a Helmholtz resonator to improve the performance of a PFEH. The resonator provides a significant improvement over the PFEH without one. The authors limit the evaluation to a relatively high frequency and express concern about designing the Helmholtz resonator for low frequencies (i.e., less than 900 Hz) without increasing the size of the device. In general, in the field of noise energy harvesting (i.e., acoustic pressure fluctuations in an air medium), an acoustic resonator can significantly improve the performance of an energy harvester. The acoustic resonator can be designed for a particular environment and frequency. The amplification of the pressure waves is a function of the material, the medium, and the design. Recently, studies in the field of acoustic energy harvesting have proposed novel structures based on complex geometries, phononic crystals, and metamaterials to improve the performance of acoustic energy harvesting \[31-34\], however, these types of devices have not been adapted to high pressure environments or high density fluids.

**Energy transducer**

Conversion of force to electrical energy can be achieved with energy converters such as piezoelectric and magnetostrictive devices. These materials can convert dynamic stress into electrical energy through the direct piezoelectric effect and inverse magnetostriction, respectively. In the context of PFEH, piezoelectric devices have gained more attention due to their simpler implementation \[35\]. In fact, piezoelectric stacks are one of the most researched devices for energy harvesting applications involving large compressive forces, off-resonance excitations, or impact events \[8, 14, 36-47\].

For example, Xu et al. \[15\] studied the piezoelectric stack for dynamic and quasi-static forces and highlighted the superior off-resonance performance of the piezoelectric stack for large force applications, compared to other conventional harvester structures, such as cantilevers. Experimental measurements show that the overall performance of the smart material is a function of the material, the design, and the quality of the device. The authors in \[8, 14\] discuss that, in practice, more volume of piezoelectric material can yield more power. However, this has a direct impact on the cost and the overall harvester volume.

In \[32\], the authors compare piezoelectric (piezoceramic), single crystal (PMN-30\%PT) and magnetostrictive (‘Terfenol-D’) stacks as shunt dampers. The experimental measurements show that single crystal stacks is the preferred transducer, with piezoelectric properties, for energy harvesting, followed by the piezoceramic and lastly the magnetostrictive. However, single crystals
are currently not as commercially available as piezoelectric ones, which complicates their widespread adoption.

![Piezoelectric structures](image)

**Figure 1.3:** Different type of piezoelectric structures for energy harvesting in large force applications.

Other transducer alternatives that may work in large force excitation applications include piezoelectric in a cymbal configuration and stacks with amplification frames [36, 47-58]. Figure 1.3 show different types of piezoelectric structures: (a) the piezoelectric stack, which is mainly composed of multiple thin piezoelectric layers; (b) the amplified stack, which is composed of a multilayer stack and an amplification mechanism, usually consisting of a steel frame that increases the force applied to the piezoelectric; and (c) a cymbal piezoelectric, which, similar to the amplified stack, is composed of a piezoelectric material between a metal frame that increases the stress in the smart material. As mentioned earlier, piezoelectric stacks have been extensively studied for off-resonance energy harvesting applications due to the high natural resonant frequency of these devices (typically > 1 kHz). On the other hand, the resonant frequency of cymbals and amplified stacks can be tuned by changing the mechanical properties of the metal frame. In terms of mechanical reliability, stacks alone can withstand very large compressive forces without breaking, but they can depolarize at large stresses [13]. For the case of cymbals, studies show that due to the large stress concentration on the piezoelectric material, it can break when the device is subjected to forces larger than its rated strength [50, 59].

**Interface circuit**

The majority of studies analyzing stack-based energy harvesters measure the AC on a matched resistive load or with a standard bridge rectifier. This method of analysis only shows the potential of energy harvester solutions, it does not reflect how much power an electronic device can use. In practice, the amount of power an electronic device can use is given by the performance of
the interface circuit, i.e. the remaining DC power delivered after rectification and conditioning.

The purpose of the energy harvesting system in an energy self-powered device is to serve as an energy source to power sensors and embedded systems. Since embedded systems cannot be powered by AC power, they require an interface circuit that rectifies and matches the AC power to a regulated DC source. In practice, the interface circuit should provide a constant voltage source, typically in the range of 1.8 V to 5 V, regardless of the input voltage generated by the piezoelectric element [60, 61].

In operation, the efficiency of the interface circuit determines how much of the harvested energy can be used by an electrical load. In addition, it can also improve coupling, resulting in higher power generation [62, 63].

The most common interface circuit for piezoelectric energy harvesting is the full-wave rectifier, which is also called standard energy harvesting (SEH) in the literature [64, 65]. Considering off-resonance operation, studies show that this topology is suitable for applications where the generated open circuit voltage is much larger than the diode voltage drop [18]. For cases where the generated open circuit voltage of the transducer is close to the diode voltage drop, alternative rectifier and interface circuits are required. Studies on power conditioning for energy harvesters with piezoelectric stacks are limited. Compared to the more common piezoelectric cantilever, the piezoelectric stack is typically characterized by a larger static capacitance, resulting in lower amplitude voltages [15], especially at low excitation forces.

Skow et al. [18] proposed using an alternative rectifier, a voltage multiplier, and a passive power improvement unit: the shunt inductor. The study considered an energy harvesting system with a piezoelectric element providing a low-amplitude voltage. Experimental results showed the advantage of the power enhancement technique and voltage amplification. This implementation was possible due to the high capacitance of the piezoelectric stack and the operating frequency (450 Hz). For low capacitance transducers or low frequency excitations, complex impedance matching can be problematic. Liu et al. [30] demonstrated a self-powered PSSH for a footstep energy harvester using a piezoelectric stack. Their implementation was limited to high voltage amplitudes due to the circuit topology using bipolar junction transistors.

The main disadvantage of the SEH is that the voltage drop caused by the two diodes in the circuit limits the input range. In addition, the output of the SEH is load dependent, which can result in low DC voltages that require voltage step-up to achieve suitable voltage levels for electronic devices.

There are several approaches to improve SEH, namely alternative rectifier topologies and power improvement techniques [66]. Researchers have investigated active power enhancement techniques for piezoelectric energy harvesting to address scenarios where complex impedance matching is impractical. The main principle of these techniques is to reduce the energy loss when charging the internal capacitance of the piezoelectric device, thereby delivering more
charge to the output. Circuit topologies that can achieve this include parallel synchronized switch harvesting on inductor [66], series synchronized switch harvesting on inductor (S-SSH1) [67], synchronized electric charge extraction (SECE) [68], and SSHI with Magnetic Rectifier (SSH1-MR) [69].

Most of the research on active power improvement units evaluates fully integrated circuits, with a few implementations considered using commercially available components. In addition, the circuits are tailored and optimized for piezoelectric cantilevers or other transducers. The studies considering active power improvement units for piezoelectric stacks are limited to [66]. Liu et al. demonstrated the use of an active nonlinear power improvement unit: the parallel synchronized switch-on inductor technique. Their analysis examined a footstep piezoelectric energy harvester with a force amplification frame that produces large voltage amplitudes (>5 V). They reported an improvement of 1.7 times the power that can be rectified by an ideal diode bridge.

In addition to rectification, an important function of the interface circuit is to regulate the voltage to a usable level to power embedded systems. There are several studies tailored to other types of energy harvesters that highlight the importance of power management for the development of self-powered devices [67], [72], [73], but studies on power management for pressure fluctuation energy harvesters are limited.

With the advances in electronics and energy harvesting technologies, several integrated circuit manufacturers have begun to offer specialized circuits for energy harvesting. However, these focus on the most common energy harvesting technologies: thermoelectric, piezoelectric cantilevers, and solar cells.

**Fully integrated self-powered systems via pressure fluctuation energy harvesting**

In a practical implementation, the PFEH in combination with the interface circuit should be able to serve as a regulated power supply, regardless of the characteristics of the ambient excitation. Full system integration of self-powered devices using pressure fluctuations has been limited to [71], [72]. In [71], the authors investigate the proof-of-concept of a self-powered system using a general energy harvesting evaluation board that provides rectification and power management. Their investigation focused on the operating conditions of a conventional hydraulic pump with pressure fluctuations at 225 Hz, 450 Hz, and 675 Hz. The energy harvester was optimised to harvest the contribution of 450 Hz, which provided about 2 bar pressure amplitude. In this scenario, their system implementation was able to produce an output power of 2.6 mW. Details of the full system integration performance, such as minimum operating voltage, were not provided.

Toothman et al. [72] considered the same environment as [71], but used a discrete interface circuit consisting of a voltage multiplier. The authors did not mention the performance characteristics of the full system integration or
the operating range of the system. Moreover, their power conditioning solution neglects voltage regulation since the output voltage is defined by the impedance of the electrical load. Despite the interest in PFEH, there are few studies on system integration with wireless devices and efficient power management as the majority of studies are focused on other type of transducers.

1.3 Problem Statement

The Pressure Fluctuation Energy Harvester presents a transdisciplinary problem involving the conversion of acoustic energy into a regulated DC power supply. Further research is required to realise a self-powered wireless system operated solely by a Pressure Fluctuation Energy Harvester. Essentially, it is necessary to evaluate in more detail the energy conversion process in the range of characteristics that describe common industrial and commercial hydraulic systems. Based on the literature, there are several shortcomings and knowledge gaps that are important for the development of a comprehensive design guide for pressure fluctuation energy harvesters. These shortcomings are discussed in some detail below, as they are believed to affect the design development of PFEH for real-world applications.

- **Characterization of PFEH**

  Previous studies have restricted their experimental and theoretical analyzes to a limited number of frequency excitations given by their experimental setup [13]. The main weakness with this approach is that the authors overlook frequency-dependent effects on pressure fluctuation energy harvesters. The standard method for investigating energy harvesting systems in more mature energy harvesting applications, such as vibration energy harvesters, consists of frequency characterization at different amplitudes [12]. So far, only single operating points have been studied in the literature. Despite the positive findings from these studies, the lack of a complete frequency analysis leads to ambiguity in the results and their applicability to other scenarios. For example, the result of Skow et. al. [19] show that the performance of the energy harvester with an acoustic resonator is highly dependent on frequency. Due to the nature of the resonator and system used, there is no way to extrapolate the results to other operating points. Therefore, there is a need for a system that allows holistic experiments on pressure fluctuation energy harvesters based on the current state of the art for other technologies. Furthermore, device characterization in pressurized hydraulic systems can be dangerous if leaks are present in the system.

- **Low-Frequency Acoustic Resonators**

  In the study by Skow et al. [19], the use of a Helmholtz resonator to enhance the performance of energy harvesters was presented. The
authors showed performance enhancement at 900 Hz, but emphasized that performance at lower frequencies was poor and even impractical. Moreover, the literature on acoustic resonators for hydraulic applications focuses only on noise reduction. The lack of studies on performance enhancement at low frequencies by acoustic resonance is a limitation in the development of PFEH for a wider frequency range.

- **Fluid-to-mechanical interface**

  The literature overlooks the influence of static pressure on the performance of the fluid-to-mechanical interface. The characteristics of the hydraulic systems expose all elements of the energy harvester to high mechanical stress. So far, all studies have considered a thin metal diaphragm as the fluid-to-mechanical interface. In practice, the PFEH would have to support high compressive forces, the reliability of the fluid-to-mechanical interface will play an important role in the design considerations of the system.

- **Power conditioning**

  Most of the research on interface circuits for power matching and performance enhancement is based on 31-mode energy harvesters or energy harvesters with other characteristics different from piezoelectric stacks, usually with lower internal capacitance, larger output voltages, or excited at resonance \[42, 53, 60, 62, 70\].

  To date, there has been limited evaluation of interface circuits for power conditioning in pressure fluctuation energy harvesters especially in stack-based energy harvesters at low excitation forces. The studies that consider stack-based energy harvesting either neglect power conditioning or use only full-wave bridge rectifiers.

  The main problem with full-wave bridges is the charge loss caused by the internal capacitance of the piezoelectric stack. First, the internal capacitance causes a phase difference between the voltage generated at the stack and the current, resulting in energy loss during conversion \[65\]. Second, the voltage amplitude may be low at low force excitation, which affects the operation of the full-wave bridge \[8, 19, 45\]. In addition, the power transfer using standard rectifiers and voltage multipliers depends on the load, that is, there is a dependency between the load and the transducer, which can limit the efficiency of the system.

- **Full System integration**

  The main goal of a PFEH is to serve as the sole power supply for electronic devices. To achieve this, it is necessary to combine different technologies and components. So far, research has focused on the analysis of the different components that make up a PFEH, there is little research
on the integration of the different elements. Although the results of
previous studies provide insight into the feasibility of Pressure Fluctua-
tion Energy Harvesting, they say nothing about the practicality of the
technology. This is especially true for systems that have lower pressure
fluctuation frequencies and amplitudes. Investigating the various com-
ponents on a larger scale, including frequencies and amplitudes relevant
to hydraulic systems, can provide researchers and system designers with
more information for the practical development of self-powered systems
via pressure fluctuation energy harvesting.

1.4 Research Objective

To build a self-powered device with a pressure fluctuation energy harvester is
necessary to study the various components to understand their characteristics
and performance. This can reveal the design requirements and predict the per-
formance. The focus of the study is on pressure fluctuations that can occur in
high torque hydraulic motors, which can have pressure fluctuations with fre-
quencies below 1000 Hz and amplitudes typically less than 10% of static pres-
sure. The main objective of this work is to investigate the various components
involved in the design of an energy harvesting system to enable self-powered
devices. This includes the characterization of the fluid-to-mechanical inter-
face, the interface circuit and the challenges for their implementation. The
results will provide insight into the performance, requirements, limitations,
constraints, and opportunities for improvement of each element of the energy
harvester as a function of external variables. The aim is to provide details and
design guidelines for the development of efficient energy harvesting devices,
thus extending previous studies in the context of pressure fluctuation energy
harvesting and self-powered systems.

1.5 Approach

In this study, a quantitative analysis method is used to develop a pressure
fluctuation energy harvester. The study is supported by computer-aided sim-
ulations and experimental evaluation.

Pressure fluctuation energy harvesting is a multiphysics phenomenon. It
involves the conversion of sound waves into electrical energy via a piezoelectric
stack and consequently into DC power.

Multiphysics finite element method (FEM) COMSOL simulations allowed
the study, parametric analysis of different components of the harvester. The
flexibility of the simulation-based study allowed constraints and tradeoffs in
the interface design to be identified before a prototype was fabricated. COM-
SOL simulations were also used to investigate different acoustic focusing meth-
ods and architectures. Compared to traditional analytical models, which sim-
pify acoustic resonator models to a simple geometry to facilitate analysis, simulations allow exploration and design of the frequency response of more complex structures.

For the analysis of the conversion of force to electrical power, circuit-level simulations enabled the study and verification of power conversion in scenarios relevant to hydraulic systems. QUCS (Quite Universal Circuit Simulator) and Micro-Cap 12 were used to simulate different topologies of power conversion circuits.

Various prototypes were designed, fabricated, assembled and evaluated. All mechanical components were designed in Autodesk Inventor considering high pressure resistant materials. Experimental studies are mainly used to evaluate ideas and verify design concepts. All experimental evaluations were performed in a custom-built apparatus capable of simulating a hydraulic environment.
Summary of Publications

This section provides a brief summary of the articles that comprise this work. The summaries highlight the contribution of each paper to the main objectives of this thesis. The full versions of the papers are appended in Part B of this thesis.


Characterization of energy harvesting is essential for research, design and development of novel energy harvesting devices. The use of energy harvesters in practise must take into account the myriad of the scenarios where energy harvesting is possible. The environmental characteristics of hydraulic systems (static pressure, fluctuation characteristics, fluid properties, temperature, etc.) vary from application to application. These variations make it difficult to extrapolate energy harvesting characterization. Instead, researchers have chosen to characterise energy harvesting devices in controlled setups to enable evaluation with controlled excitation. To advance state-of-the-art characterization of energy harvesters with pressure fluctuations, we developed a custom apparatus for device characterization. Compared to previous studies where the energy harvester was subjected to a single scenario (pressure fluctuation generated by a pump), our apparatus can vary the main variables of the application. The system allows the selection of the different variables that can define a hydraulic system, i.e. static pressure, fluid properties and pressure wave characteristics. The apparatus allows the characterization of pressure fluctuation energy harvesters at deterministic and custom pressure fluctuation. The main features of the apparatus are:

- Controllable static pressure.
- Generation of pressure fluctuation with different characteristics
• Replication of signals from real-life environments.

The device is limited to a static pressure of 300 bar due to the mechanical characteristics of the components. The system can monitor the pressure characteristics and accommodate an Energy Harvesting device. However, it can only accommodate an energy harvesting device with a standard hydraulic connection.

**Author Contribution:** Conceptualization, mechanical design, apparatus development, manuscript writing and editing.

### 2.2 Paper II: Fluid Coupling Interfaces for Hydraulics Pressure Energy Harvesters. *In Proceedings of the the Int. Conf. on Advanced Intelligent Mechatronics. (AIM)*

A critical component of the pressure fluctuation energy harvester is the interface between fluid and mechanics. This work is an exploratory study based on computational simulations to evaluate the role of pressure in the behaviour of the fluid-mechanical interface. The study considers a single metallic plate subjected to pressure and evaluates the transmission of force. The metallic plate is critical to the operation of the energy harvester. It not only converts pressure fluctuations into force, but also isolates the transducer from the fluid. High concentrated stresses can cause the plate to fracture and cause leaks in the system. Therefore, careful sizing and design of the plate is required. The most important variables of the interface are diameter, thickness, and exposed area. The exposed area is the area that has no support, that is, it can bend and break. In this study, it was found that thicker interfaces can withstand higher static pressure and protect the stack from stress, however also limit the performance of the energy harvester. In low-pressure systems, the interface allows higher interface area, which can increase power but can be at risk if pressure spikes are present. This work informs on the requirements of the interface, e.g., required mechanical properties to stand high pressure forces. The results of this study were a starting point for evaluating various fluid-to-mechanical interfaces. It also raised questions about the influence of pressure fluctuation frequency and possible improvements of the fluid-to-mechanical interface.

**Author Contribution:** Conceptualization, simulations, manuscript writing and editing.

The study is motivated by the results of PAPER II, where frequency dependence was not considered. The interfaces considered in this work are a flat metal plate with a metallic spacer and a hydraulic piston. The metallic spacer was added to the metallic plate to reduce the stress and increase the performance, based on the previous analysis. The interfaces were studied under conditions relevant to conventional hydraulic systems. Experimental analysis showed that the flat metallic plate did not exhibit any significant frequency dependence in the investigated range. However, it showed a decreasing force transmission ratio with increasing static pressure. The metallic plate also showed failure at high static pressure, as a result of concentrated stress at the edge of the plate. On the other hand, the hydraulic piston with different o-rings showed that the transmission ratio decreases for increasing frequency. This effect was attributed to the damping effect of the seals used in the design of the piston and misalignment. The piston offered better capabilities for high static pressure situations, making it a better alternative for scenarios with low frequency peak-like pressure fluctuations. Overall the plate showed to be more versatile, despite its shortcomings, since it can be easily adapted to accommodate different environments and is easier to implement.

**Author Contribution:** Conceptualization, prototype design, prototype development, experimental analyses, manuscript writing and editing.


The literature shows that the power generated by the PFEH is proportional the square of the amplitude of the pressure fluctuation [18], [19]. Thus, improvement in power generation can be achieved either by increasing the area of the fluid-to-mechanical interface (which also increases the static load on the transducer and interface) or by increasing the pressure fluctuation amplitude. The latter can be achieved by acoustic resonance which only amplifies dynamic pressure and not static pressure. In previous studies [15], the Helmholtz resonator was presented as a potential device to increase the power generation of the PFEH. However, Helmholtz resonators design is challenging for hydraulic applications with low frequency excitation. In this work, a new acoustic resonator for hydraulic systems has been presented that can achieve lower resonant frequencies without increasing the overall volume.
This study compared conventional Helmholtz resonators and the space coiling resonator for different frequencies. The study showed that the space coiling resonator can provide better acoustic amplification than the Helmholtz resonator for the same volume. The fabrication of the resonator was possible using 3D printing techniques that allow the development of complex geometries that enable the lowering of the resonant frequency. Simulation and measurements showed that the space coiling resonator can yield better performance for the same volume, thus proposing a viable alternative to classical Helmholtz resonator.

**Author Contribution:** Conceptualization, prototype design, prototype development, experimental analyses, manuscript writing and editing.

### 2.5 Paper V: Power Conditioning for Pressure Fluctuation Energy Harvesters Using Piezoelectric Stacks Under Low Excitation. *(In Manuscript)*

A major disadvantage of using pressure fluctuation energy harvesters in low excitation situations is effective power conditioning. The majority of studies with piezoelectric stacks or cantilevers consider mainly large voltage outputs. This paper evaluates the performance of various interface circuit configurations consisting of different rectifier circuits, power enhancement circuits and a power management circuit. The results show that the operating range and efficiency of pressure fluctuation energy harvesters can be improved by using a step-up rectifier circuits, such as a voltage doubler and voltage quadrupler.

In addition, we have demonstrated two circuit techniques for performance improvement tailored for low-voltage scenarios. This work shows that depending on the voltage amplitude and frequency (related to the application), the performance can be optimized by choosing the right rectifier circuit and power enhancement technique. The results of this study enable the design and optimization of pressure fluctuation energy harvesters for a wider range of applications, thus extending previous studies.

### 2.6 Paper VI: Self-Powered Wireless Sensor Using a Pressure Fluctuation Energy Harvester. *(In Sensors)*

The main goal of an energy harvesting device is to serve as the main power supply for electronic devices. In the context of the Internet of Things, energy harvesting devices are key components for the development of wireless sensor systems. Harvesting energy from the environment can eliminate wired infrastructures and batteries. This work integrates the findings from the other studies presented in this thesis into a prototype that demonstrates the operation of a self-powered wireless sensor system. This work main contribution is the development of a complete self-powered device using a pressure fluctuation
energy harvester. The developed device shows the advantages of the different improvements on the PFEH and how it benefits in the self-powered operation. The system uses the results of previous studies and analyzes the constraints and influence of the different components that comprise the energy harvester. The work shows that by integrating the space coiling resonator, and a low-voltage power improvement circuit, the energy harvesting performance of the PFEH can be further improved. In addition, this study shows the trade-offs and characteristics of a wireless pressure sensor fully powered by the energy harvester and the achievable sampling rate of the system. The results of the analyzes show that a PFEH can power a wireless sensor system even at low pressure fluctuation and frequency.
Theory

3.1 Pressure fluctuation in Hydraulic Systems

Noise in hydraulic systems is an undesirable byproduct of system operation. The dominant source is the pump, although other elements in the system (e.g., pistons, valves) may also contribute to noise generation and transmission. Noise can be classified as fluid-borne (FBN), structural borne noise (SBN), and air-borne (ABN). Positive displacement pumps generate pressure pulsations as a result of superimposed flows. The fluctuations generate FBN that propagate through the system and vibrate all downstream elements. Similarly, the pump generates SBN as a result of the vibrations in the mechanically connected components, e.g. brackets, covers. The transmission of the fluid and structure-induced vibrations to the adjacent air boundary results in ABN. The frequency and amplitude of noise propagated in hydraulic systems are directly related to the operation of the pump and vary depending on the measurement location. Fig. 3.1 shows a general representation of FBN, SBN and ABN.

PFEH can harvest propagating plane waves within the fluid, which can be FBN or SBN, by coupling the fluid into a mechanical-to-electrical energy transducer. Compared to noise in air, the intensity of hydraulic noise can be up to an order of magnitude higher. This is a direct result of the properties of the medium. However, compared to EH in air, PFEH must withstand static pressure that is not present in air. This limits the design of the PFEH.

Moreover, static pressure limits the design of PFEH in terms of the fluid-to-mechanical interface. Power intensity is measured as energy per area, suggesting that a PFEH with a larger exposed area can produce more power. However, a larger interface area also implies a higher compression force, which may adversely affect the interface and the transducer. Consequently, studies have shown the possibility of improving the performance of PFEH without increasing the area of the fluid-mechanical interface by using acoustic resonators.
3.2 Energy focusing methods for pressure fluctuations energy harvesters

The performance of the PFEH can be improved through acoustic resonators. A common acoustic focusing device is the Helmholtz resonator (HR), which can amplify pressure fluctuations at a given frequency. The HR consists of a narrow neck that connects to a cavity, as shown in Fig. 3.2.

Assuming that the characteristic dimensions of the resonator are smaller than the wavelength of the pressure fluctuations (on the order of meters for 1000 Hz), the resonator can be modeled by "lumped-element" parameters. The electrical analogy, represented as an RLC circuit, is shown in Fig. 3.2. The neck of the HR is modeled as an inductive element ($L$) and the cavity as
a capacitor \((C)\). \((R)\) is the acoustic resistance. The resonant frequency of the system, for low concentration of air, can be estimated by \([15]\)

\[
f_{\text{res}} = \frac{1}{2\pi} \sqrt{\frac{d_{\text{neck}}^2 c^2 f}{l_{\text{neck}} l_{\text{cav}} d_{\text{cav}}^2}}
\]  

(3.1)

Most of the acoustic losses are related to the narrow neck (viscous losses), damping losses in the material and hydraulic fluid, and acoustic radiation losses \([15, 26, 75, 77]\). From (3.1) it can be seen that the resonance of HR can be reduced either by increasing the volume cavity \((l_{\text{cav}} d_{\text{cav}}^2)\), the length of the neck \(l_{\text{neck}}\), or decreasing the neck’s diameter \(d_{\text{neck}}\). In practice, increasing the volume of the cavity or the length of the neck may result in an infeasibly large device. On the other hand, decreasing the neck diameter has a negative effect on the gain \([15]\).

### 3.3 Energy Harvesting via Multilayer Piezoelectric Stacks

Piezoelectric devices are smart materials that can convert mechanical energy into electrical energy through the direct piezoelectric effect. Piezoelectricity is the electric charge that accumulates in some solid materials. In crystalline materials without inversion symmetry, for example, the piezoelectric effect arises from the linear electromechanical interaction between mechanical and electrical states. This process is reversible, which means that if a material exhibits the direct piezoelectric effect, it also exhibits the reverse piezoelectric effect \([48, 53, 78]\). For example, lead zirconate titanite (PZT) materials produce piezoelectricity when their structure is deformed, and vice versa. Piezoelectric stacks are often used as actuators in small deflections, high forces and high precision.

A multilayer piezoelectric stack is a device composed of thin layers of PZT material. The stack generates electrical energy as a result of an applied force. In principle, an electric current is generated as a result of the disturbed charge balance when subjected to an external stress. In recent years, these devices have found application in energy harvesting scenarios where other popular PZT structures (e.g., cantilevers) cannot be used. Compared to cantilevers, piezoelectric stacks can withstand higher compression forces without breaking and offer better off-resonance energy harvesting capabilities. For piezoelectric devices used for energy harvesting, there is a specific polar axis that determines how the system works. Piezoelectric stacks operate in ’33-mode’, which means that the force is applied in the direction of the poling of the piezoelectric. Fig. 3.3.
Figure 3.3: Piezoelectric generator modes.

The piezoelectric stack is the parallel combination of multiple layers of piezoelectric material. The generated charge in each piezoelectric plate in response to a force is

\[ Q = d_{33} F \]  \hspace{1cm} (3.2)

where \( d_{33} \) is the effective piezoelectric coefficient in the 33 direction and \( F \) is the force. The charge generated in the stack can be estimated by

\[ Q_{\text{stack}} = nd_{33} F \]  \hspace{1cm} (3.3)

where \( d_{33} \) is the effective piezoelectric coefficient of a single layer and \( n \) is the number of layers. The equivalent piezoelectric coefficient of a piezoelectric stack can be estimated by

\[ d'_{33} = cn d_{33} \]  \hspace{1cm} (3.4)

where \( c < 1 \) is determined by the construction and properties of the stack. \( c \) is dependent on the configuration and construction of the stack with typical reported in the range of 70% to 95% [45].

In the same manner, the capacitance of the stack is the combination of the capacitance of each layer.

\[ C_{\text{stack}} = n \varepsilon_r \varepsilon_0 \frac{A}{l} \]  \hspace{1cm} (3.5)

\( \varepsilon_0 \) and \( \varepsilon_r \) are vacuum and relative permittivity of the material, respectively. \( A \) and \( l \) are the area and thickness of the piezoelectric layer. For off-resonance
operation, the open-circuit voltage is obtained by the voltage charge relation

\[ v(t) = \frac{Q(t)}{C_{\text{stack}}} = \frac{nd_{33}F(t)}{C_{\text{stack}}} \]  

(3.6)

In essence, time-dependent voltage is generated by the change of charge in the stack as the result of an applied force.

The generated electrical power, for a sinusoidal force, can be estimated by

\[ P_{AC} = \sqrt{2\pi f C_P V_{\text{rms}}^2} \]  

(3.7)

### 3.4 Power Conditioning

![Circuit model of a off-resonance piezoelectric stack energy harvester](image)

A piezoelectric transducer subjected to a time-varying mechanical excitation can be electrically modeled as a current source in parallel to a capacitor and a resistor as seen in figure 3.4. The resistance is analogous to the loss factor of the material and \( C_p \) is the capacitance of the stack. Assuming a sinusoidal excitation, the current generated can be estimated according to \( 45 \) by

\[ I_p = \omega d_{33}^* F \cos(\omega t) \]  

(3.8)

For a stack connected to a resistive load the maximum delivered electrical power is \( 45 \)

\[ P_L = \pi f C_P V_{\text{rms}}^2 \]  

(3.9)

To be able to use the power generated by the piezoelectric stack, the time-varying voltage generated by the stack must be rectified. For a sinusoidal excitation, the total amount of charge generated by piezoelectric stack every half cycle is

\[ Q_{\text{stack}} = 2C_P V_p \]  

(3.10)
The cumulative charge that can be delivered to an electric load depends on the rectifier circuit. For the case of the full-wave bridge rectifier, the operation is shown in figure 3.5.

Figure 3.5: Waveforms of the operation of the full-wave bridge rectifier

Considering half cycle of operation, the inner capacitance of the stack is charged up to \( V_{DC} + 2V_D \) before the bridge rectifier can conduct. The amount of charge lost during this process (represented as the white portion of the waveform of \( I_p \) in figure 3.5) can be determined by

\[
Q_{lost} = 2(V_{DC} + 2V_D)C_p
\]

(3.11)

The rectified power can be calculated as the difference between the total charge and the charge loss in the inner capacitance, this results in

\[
P_{DC} = 2fV_{DC}(Q_{stack} - Q_{lost}) = 2C_p fV_{DC}(2V_p - 2(V_{DC} + 2V_D))
\]

(3.12)

Finding the maximum power, one can find the optimal voltage for power transfer as

\[
[FBR]\quad V_{DC}^{opt} = \frac{V_p}{2} - V_D
\]

(3.13)

One of the main drawbacks of the full-wave bridge as a power conditioning circuit is that the open circuit of the transducer must be at least \( V_p > 2V_D \), which limits the operating range. Also, in practise, the output voltage must be much higher than \( 2V_D \) to be suitable for powering electronic devices.

Thus, to increase the power generation of a piezoelectric stack different techniques to reduce \( Q_{lost} \) must be used. For instance, passive techniques such as shunt inductor or circuit techniques such as synchronized switching.
techniques, which aim to reduce the charge loss in the internal capacitance of the stack \[61, \ 65-69, \ 81\].
Discussion

In this section, issues related to the pressure fluctuation energy harvester are discussed based on the results presented in the papers. The discussion focuses on the findings, contributions and limitations of the work presented. This section is divided into several subsections dealing with various studies and components of the harvester, mainly the experimental apparatus, acoustic resonator, fluid-to-mechanical interface, piezoelectric stack, energy conditioning, and system integration.

4.1 Experimental Apparatus

The apparatus developed in this work allowed the exploration and characterization of different PFEH prototypes. This apparatus greatly improves the systematic study of PFEH. Compared to previous studies, our proposed experimental setup enables a more comprehensive characterization of PFEH in a variety of combinations. This proposed experimental setup can serve as a basis for further improvements.

The main limitations of this experimental setup are as follow:

- The performance of the actuator, and the driver is a limitation. Pressure fluctuations are generated by a linear actuator (piezoelectric actuator), which has two main limitations, namely maximum compression strength and heating in dynamic operation. These limitations restrict the performance of the device in the maximum tolerable static pressure and in the maximum possible excitation frequency. Cooling can increase the operating range of the actuator. A linear actuator with a larger cross-sectional area would be able to withstand higher pressure forces.

- Variation of oil properties. The properties of the hydraulic fluid used in all experiments depend on static pressure, temperature, air content, contamination, and age. To minimise differences in oil properties, the same brand and type of oil was used for all experiments. Commercial oil was
used for all experiments to minimise the variables of age and contamination. However, different hydraulic applications use different types of hydraulic fluids under different wear, temperature, and air content conditions. More accurate modelling of hydraulic fluid could improve the modelling of PFEH when high accuracy modelling is required under different conditions. Nevertheless, air content and variability of the oil are expected properties in real applications.

### 4.2 Energy Harvesting via Multi-layer Piezoelectric Stack

In this work, the multilayer piezoelectric stack is the core component of the energy harvester. Meanwhile, this transducer has been used in other applications that exhibit large compressive forces, off-resonance excitation, or in shock events [13, 22, 37–40, 45, 51]. These studies have demonstrated the capabilities and advantages of piezoelectric stack compared to other structures [14]. However, one of the major current uncertainties regarding the piezoelectric is its reliability.

To date, there are few studies investigating the reliability and lifetime of the multilayer piezoelectric stack in energy harvesting applications. Theoretically, the stack is ideal for applications with large compressive forces due to its compressive strength. Nevertheless, empirical observations during the experiments showed that due to the brittle nature of the piezoelectric material, small fractures in the stack can lead to failure of the PFEH. These observations are supported by the results of Ende et. al. [87]. Some studies investigate the reliability and lifetime of the stack as an actuator. The literature shows that the stack lifetime is more than 11 years for full-range operation with decreasing performance thereafter [87, 88]. Failure can occur either by cracks in the material or by stress-induced depolarization. In addition, studies show that piezoelectric materials can be depolarized by static and cyclic stresses [89], resulting in a decrease in energy harvesting capabilities. This effect is also expected for the piezoelectric stack, but the extent of depolarization is uncertain for energy harvesting applications.

### 4.3 Fluid-to-Mechanical Interface

The results of the analyses concerning the fluid-to-mechanical interfaces can be used as a design basis for PFEH. The most important variables to consider in the design of a fluid-to-mechanical interface are the static pressure and the frequency of pressure fluctuations.

For systems with high static pressure, there are two alternatives: Hydraulic pistons and flat metal plates.
• **Hydraulic Pistons** When high static pressure is expected in a system, it is recommended to use a hydraulic piston as the main interface. These interfaces have higher reliability compared to metallic plates. Therefore, they are ideal for applications where high pressure peaks may occur. For example, when water hammer is expected in an application. The main limitation of the hydraulic piston is its design and construction. Ideally, the piston should have low damping with increasing frequency. This requires a high quality piston design. This would mean optimizing the size and material of the seal used. In practice, the design and assembly of the piston is more difficult and oil leakage into the transducer can occur.

• **Flat Metallic Plate**. This interface is the most versatile of those studied and used in other studies [3], [4], [7], [9]. The plates can be paired with a metallic spacer. For low static pressures, plates without spacers can be used. In these cases, it is shown that the pressure-force transfer relationship depends on the plate thickness. The choice of plate area and thickness is also a trade-off between maximum static pressure and power generation. A larger area would result in higher power but may compromise the integrity of the plate. These results suggest that the plate without spacer can be an alternative for PFEH in low pressure applications. In addition, recent analytical and experimental studies by Xiao et al. [9] show that a centrally loaded flat metal plate can exhibit damping hardening behavior in a force-deflection relationship. These new results suggest that the flat metal plate without spacer can find applications in nonlinear energy harvesting applications, which extends our previous conclusions. The results suggest that plates with a metallic spacer exhibit the greatest versatility of the interfaces studied. These interfaces show better transmission efficiency than previous configurations, especially at low static pressure conditions and without significant frequency dependence. Similar to the plate without spacers, there is a trade-off between stress concentration and maximum compressive strength. Further empirical observations suggest that the shape of the spacer and the flat metal plate can be optimized to increase the transmission ratio and improve the reliability of the plate. As discussed in Paper III, the plate can fracture at high pressures due to the concentrated stress on the plate. Physical modifications to the plate can reduce these stresses and increase the maximum stress that the plate can withstand. Essentially, testing has shown that a flat interface may not be the ideal for PFEH, so it is recommended that convex and concave membranes be investigated, which may have different behavior than flat fluid mechanical interfaces.
4.4 Acoustic Resonators

In Paper IV, a resonator structure is studied to improve the energy generation of the pressure fluctuation energy harvester. Simulation and experimental verification showed that the space coiling resonator can achieve lower resonant frequencies than the classical Helmholtz resonator with the same volume and improve the energy harvesting performance compared to a PFEH without resonator. Thus, it represents an important contribution to the improvement of pressure fluctuation energy harvesters.

The design of the acoustic resonator depends on the dominant frequency of pressure fluctuations in a hydraulic system. In general, the energy generation for the PFEH is proportional to the square of the dynamic pressure amplitude. Therefore, the choice of the dominant frequency is crucial for the design of the resonator, since conventional hydraulic systems usually have more than one pressure fluctuation frequency. As the results suggest, larger acoustic gains are more easily obtained at higher frequencies (for the same occupied volume). For example, if a system has two dominant frequencies, even if the pressure amplitude of the high-frequency component is smaller than that of the low-frequency component, more power can be gained from the larger frequency component [17]. Thus, it is obvious that the selection of the design frequency is not trivial. Moreover, the resonant frequency has an impact on the selection of the power conditioning circuit.

So far, space coiling resonators have only been fabricated using multi-jet fusion 3D printing technology. This technology is one of the few 3D printing techniques that allows the development of complex structures with internal extrusion. This limits the possible printed materials. Harder materials (e.g. metals) and smoother walls could provide greater acoustic gain. It is expected that as 3D printing techniques evolve, more materials will be supported by this technology. This will allow research and characterization of the effect of the material on the resonant frequency and gain of the space coiling resonator. The comparison of the proposed design with the literature is challenging due to the different characteristics of the fluid properties and the environment that can affect the behaviour of the system. Nevertheless, the analysis shows that the resonator is a promising alternative to the classical structure.

One of the main limitations in the development of the space coiling resonator is the lack of an automated design. In Paper IV, an iterative design process was used. This process requires computer-aided modelling and simulation to arrive at the final design. A more detailed analytical model or procedural generation of the 3D model would significantly streamline the development of resonators for PFEH.
4.5 Power conditioning

Power conditioning for piezoelectric stacks is critical in the design for PFEH because it defines the power delivered to an electrical load. Moreover, some circuit techniques can actually increase the power that can be extracted from the piezoelectric stack. Power conditioning mainly consists of rectifying and regulating the voltage. In this work, power conditioning is implemented using commercially available circuit components. Voltage rectification has been analysed using a full-wave bridge rectifier, a voltage doubler and a voltage quadrupler. Voltage regulation is studied using a commercial DC-DC integrated circuit. In paper V, different configurations of interface circuits are discussed under different conditions. The results show that the performance of the PFEH is highly dependent on the power conditioning circuit.

Similar to the resonator, the power conditioning circuit also depends on the frequency of the pressure fluctuations. In addition, the circuit design and power generation performance also depend on the open circuit voltage. In order to generate a stable power source for electronic devices, the results suggest that there are two main metrics that describe a power conditioning approach: performance of the rectification and operating range of the power conditioning circuit. The first refers to a metric that describes the rectified power compared to the power obtained with an ideal full-wave bridge [16]. The latter refers to the minimum conditions required to act as a voltage source regardless of the input. The minimum conditions are a function of the rectifier and the DC-DC integrated circuit.

The analyses in paper V identify several scenarios in power conditioning for PFEH, which are summarised below.

- **Case A: High frequency and large open-circuit voltage amplitude.** The results in this work as well as the results in [15], [17], [20] show that power conditioning in this scenario benefits from the voltage doubler or quadrupler with either a parallel synchronized switch on inductor or a shunt inductor. Paper V shows that at high frequencies, shunt inductor is a viable technique to improve the performance. The advantage of shunt inductance over PSSHI is the passive nature of the power improvement technique. The analyses show that the shunt inductance in this scenario not only increases the power generation but also increases the operating range of the PFEH.

\[1\text{Low frequency refers to the pressure fluctuation }<300\text{Hz. Large amplitude open-circuit voltage refers to cases where the PFEH delivers open-circuit voltages }>1\text{V.}\]
– **Case A: High frequency and open circuit voltage with small amplitude.** Similar to the previous scenario, shunt inductance is the best option to enable harvesting from low amplitude sources. The proposed circuit for PSSI presented in Paper V showed improvement, however its more significant at large open-circuit input voltages.

– **Case A: Low frequency open circuit voltage with large amplitude.** The PSSI power improvement technique requires smaller inductors than the shunt inductor technique. Therefore, PSSI can have better performance at lower operating frequencies.

– **Case A: Low frequency, low voltage amplitude.** This is the most challenging scenario for energy harvesting. Analysis has shown that a rectifier with voltage step-up (voltage doubler or quadrupler) is mandatory to enable a commercial DC-DC voltage regulator. The full wave bridge is not an option in this scenario. The choice of the power enhancement is mainly based on the size constraints of the application.

**Power improvement techniques**

A critical component of the rectification process is the power improvement circuit. In Paper V, two main power improvement circuits are investigated: the shunt inductor and the parallel synchronized switch harvesting on-inductor. In the previous section, different scenarios and overall performance of the power improvement techniques have been described. Apart from the voltage amplitude and frequency dependence, these techniques are highly dependent on the implementation, i.e., the quality factor of the physical inductance and the precision of the circuit design.

– Shunt inductor: the shunt inductor can increase the power generation of the PFEH at any frequency and voltage amplitude. Moreover, it does not require external power for operation. The main limitation is the inductor quality factor, i.e., it is mainly affected by the parasitic resistance of the inductor. In practice, this means that a high Q factor inductor can be large (in volume) [17]. Thus, if the application has no volume constraint, the shunt inductor would be a better alternative to the PSSI.

– Parallel synchronized switch on inductor: the results from Paper V show that the parallel synchronized switch on inductor is strongly dependent on the voltage amplitude and the quality of the inversion process. Similar to the shunt inductance, the PSSI performance changes when the frequency of the pressure fluctuation changes.
However, the change is not as significant as for shunt inductance. Moreover, the PSSH1 is a better alternative for applications where small-volume inductors are required.

The main limitation of the PSSH1 is the active nature of the circuit. This power improvement technique only works when it is powered. For fully energy-autonomous operation, this means that the PFEH cannot benefit from the PSSH1 until there is sufficient power to turn on the PSSH1.

**Voltage regulation and Power Management**

Voltage regulation and power management are critical to produce a stable voltage source that is independent of the input and load. In Paper V, we considered a commercial power management circuit designed specifically for energy harvesting devices. The voltage regulation directly affects the operating range of the PFEH, i.e., the minimum open-circuit voltage required to operate the power management circuit. The shunt inductance technique and the rectifier with voltage step-up characteristics can extend the operating range of the PFEH.

The limitations introduced by the power management circuit are more evident in low energy density scenarios (low pressure amplitude, low frequency).

### 4.6 Full system integration

Advances in low-power wireless systems are enabling the development of energy self-sufficient systems powered by energy harvesters. In the case of the PFEH, full system integration includes the combination of an acoustic resonator, a fluid-to-mechanical interface, a transducer, power conditioning circuit and power management. To date, the studies described in this paper have considered the components of the PFEH separately and proposed techniques and methods to improve power generation and operating range. To demonstrate the impact of these advances, Paper VI discusses and highlights the challenges in developing wireless sensor systems powered by a PFEH. The results show that the advances discussed in this work can extend the operating range of self-powered devices employing PFEH as their source of power.
Conclusion

With the impending fourth industrial revolution and the Internet of Things, the need for battery-less wireless systems is more necessary than ever. The main objective of this work was to study the challenges, methods and techniques involved in the implementation of pressure fluctuation energy harvesters as a self-powered power supply.

A self-powered system powered by a pressure fluctuation energy harvester involves the conversion of acoustic energy into a regulated voltage source. In this work, the individual components of the energy harvester were analyzed and their role in power generation was investigated. First, a bespoke experimental setup was developed to characterize pressure fluctuation energy harvesters. This system allowed more diverse experimentation on energy harvesters. This development contributed to the characterisation of pressure fluctuation energy harvesters and can be further developed and adapted to allow exploration of other designs and ideas.

To investigate the conversion of pressure fluctuations into electrical energy, studies were presented on the interfaces for the conversion of acoustic pressure into electrical energy. Simulation and experimental verification showed a dependence of the fluid interface mainly on pressure. The results extended previous studies by revealing more information about the nature of the interfaces and the expected performance, as well as details about their mechanical limits. This enables the formulation of basic design guidelines for the fluid-to-mechanic interface as a function of hydraulic system parameters, thus extending previous studies.

Another contribution in the field of fluid-to-mechanic interface, is the 3D printed space coiling resonator, which can increase the pressure fluctuations and thus increase the power generation. Simulation and experimental evaluation showed that the proposed structure can provide improved amplification, compared to a classical Helmholtz resonator of the same volume. This study opens the possibility for further research in the field of 3D printed acoustic resonators for energy harvesting in hydraulic systems.

Moreover, the analyzes on various interface circuit for stack-based energy harvesting circuits revealed the limitations, challenges and trade-offs in volt-
age rectification and power management. This involved the investigation of various interface circuits to extend the operating range of Energy Harvester to applications that have low-amplitude pressure fluctuations. This study can be used as a basis for designing current conditioning circuits for stack-based energy harvesters.

Furthermore, this work shows that by integrating the developed results, methods and techniques, it is possible to design and develop a self-powered wireless sensor system even in low energy density systems. Thus, the main objective and the research goal of this thesis are fulfilled.

Overall, the results can serve as a design guide for the development of pressure fluctuation energy harvesters for conventional hydraulic systems.

5.1 Future work

In the study of acoustic energy harvesting in a fluid medium, several research directions arise in relation to fluid-to-mechanical interfaces. Recent studies \cite{14, 83} have extended our research and demonstrated that nonlinear behaviour can be achieved in fluid-to-mechanical interfaces. Therefore, further research on interfaces for low static pressure systems may reveal more applications and scenarios where the exploitation of pressure fluctuations is possible.

The studies have shown that the space coiling resonator is an interesting alternative to conventional Helmholtz resonators. With the advances in 3D printing technology, further research on these devices can improve the acoustic gain and resonant bandwidth. In addition, a more comprehensive study on the material influence of the resonator can shed light on the possibilities of material manipulation to optimise the acoustic gain.

More efficient circuit designs, especially at low frequencies and low pressure amplitude, are needed. This could include integrated circuit design. In addition, performance enhancement solutions that do not require physical inductors may improve interface circuit miniaturisation.

For hydraulic systems where pressure variations may be intermittent, alternative power management solutions are required. In addition, smarter, i.e., energy-aware, solutions for integrating pressure fluctuation energy harvesters with wireless sensor systems can significantly improve the practicality of the advances demonstrated in this work.
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