Acoustic energy transmission in cast iron pipelines

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Abstract. In this paper we propose acoustic power transfer as a method for the remote powering of pipeline sensor nodes. A theoretical framework of acoustic power propagation in the ceramic transducers and the metal structures is drawn, based on the Mason equivalent circuit. The effect of mounting on the electrical response of piezoelectric transducers is studied experimentally. Using two identical transducer structures, power transmission of 0.33 mW through a 1 m long, 118 mm diameter cast iron pipe, with 8 mm wall thickness is demonstrated, at 1 V received voltage amplitude. A near-linear relationship between input and output voltage is observed. These results show that it is possible to deliver significant power to sensor nodes through acoustic waves in solid structures. The proposed method may enable the implementation of acoustic - powered wireless sensor nodes for structural and operation monitoring of pipeline infrastructure.

1. Introduction

Monitoring the condition and operation of infrastructure in industrial plant, transportation and distribution networks are important application areas for emerging Internet of Things technologies. This application is important because it can reduce operation and maintenance costs, improve service availability and introduce reliable safety and security mechanisms. It can also enable new services, including centralized industrial control and intelligent control of resource networks. The implementation of such systems is increasingly becoming economically beneficial, for a variety of applications, in terms of utilization, reliability and insurance, but also in environmental and infrastructure security terms.

The development, installation and operation of continuous monitoring systems for infrastructure such as aircraft engines [1], urban trash collection [2], oil and gas pipelines [3] and intelligent transportation systems [4] has progressed rapidly in recent years largely due to the maturity of wireless communications. A challenge in the broad adoption of permanent monitoring installations is powering the sensor nodes involved, especially when deployed in large numbers and/or at inaccessible locations. For this purpose, considerable attention has been attracted to the development of low-power electronics and high-density batteries for wireless sensor nodes. Ultimately, a maintenance-free permanent monitoring system requires energy autonomous wireless nodes, which is achievable by harvesting energy from the local environment [5], using a radioactive power source [6], or wireless power delivery [7, 8]. For the latter, power can be delivered in various ways, the most commonly proposed in recent publications being via inductive coupling and via vibrational waves. Other possible means include electromagnetic radiation, light, heat and low-frequency motion and vibration.

Here, acoustic energy transmission through metal pipes is studied and assessed as a method for powering sensor nodes located on the outer pipe surface. This is relevant to monitoring applications involving pipeline structures, such as gas, oil, water, and sewage networks, and also industrial environments such as plant, production and mining sites.

2. System concept

The objective of the proposed system is to remotely power wireless sensor nodes that are installed on the surface of a pipe, by transmitting a vibration wave along the pipe walls; shown in in Fig. 1. The system consists of a vibration exciter, which induces a transverse, longitudinal or shear vibration wave into the pipe structure. The vibration propagates down the pipe through the pipe walls, the contents and the surrounding material. Each wireless sensor node is equipped with a vibration harvester, which can be inertial or direct-force-based, depending on the installation requirements. The received energy is transduced into electrical form and, subsequently, it is either used directly or accumulated in intermediate storage. In this work the exciter and sensor/harvester are piezoelectric transducers.
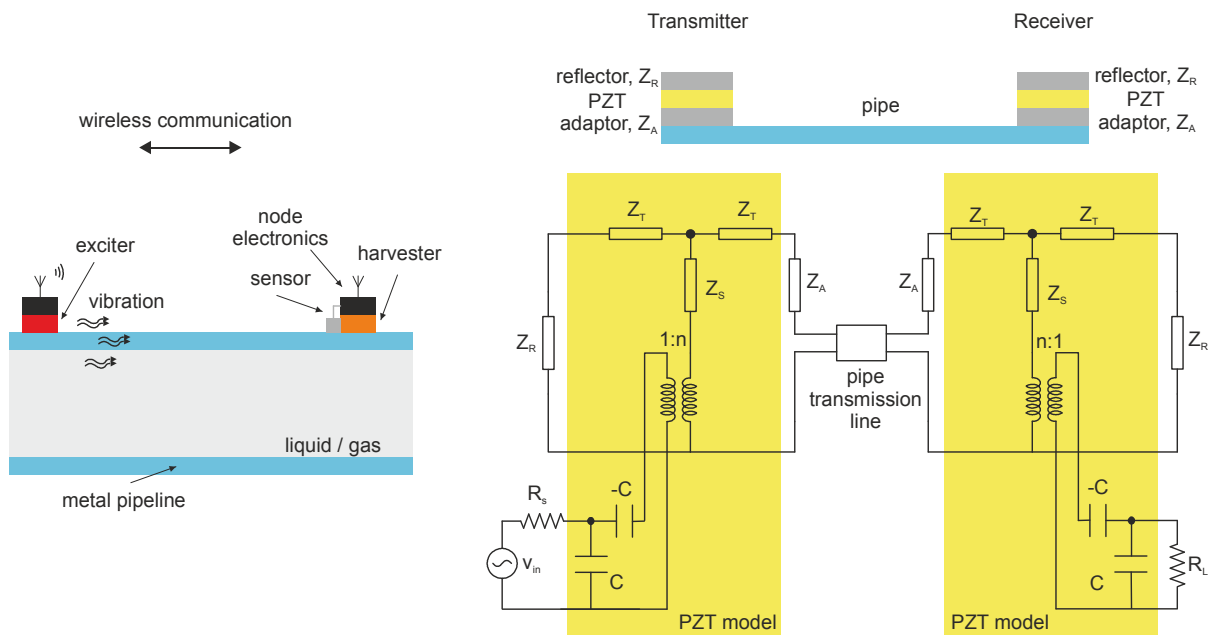

Figure 1: Left: Conceptual description of the proposed powering method. Right: Model of acoustic power transmission based on the Mason equivalent circuit.

3. Theoretical background

Acoustic properties of pipeline structures have been rigorously studied in developing methods for structural characterization, and especially for the non-invasive measurement of inner corrosion in metal pipes [9]. Driven by a large commercial market, this work has been extended to include simulation and analytical tools, providing a strong theoretical and experimental background [10, 11].

In support of the discussion of the experimental results in this paper, an outline of a simple lumped-element modelling method, based on the Mason model [12] for piezoelectric transducers and a T equivalent circuit for acoustic transmission lines is given below. It is noted that in this model, as a first approximation for vibration transmission at low frequencies, the pipe structure is treated as a bulk material. The corresponding lumped-element circuit is shown in Fig. 1 (right).

The case of using identical transducers for the transmitter and the receiver is analysed, as illustrated in the right-top of Fig. 1. Each transducer consists of a PZT crystal with area A, thickness τ, dielectric constant ε, bulk modulus K and density ρ. An adaptor layer is used between the crystal and the pipe, while a reflector layer is used on top, allowing for acoustic impedance matching. The pipe structure is treated as a bulk material, with non-dispersive wave propagation. This means that a constant PZT sound speed $v_{PZT} = \sqrt{K/\rho}$ can be assumed for all frequency values. The specific acoustic impedance quantity, denoted as Z in Fig. 2, is defined as the ratio of force over velocity, with unit N / (m/s). The Mason model specific impedances, for zero attenuation, are $Z_T = jZ_0\tan(\Gamma\tau/2)$, $Z_S = -jZ_0\csc(\Gamma\tau)$, $Z_0 = \rho \cdot v \cdot A$ and $\Gamma = \omega/v_{PZT}$, where ω is the wave angular velocity [12, 13]. The transformer factor

is $n = g \cdot C \cdot K$, with unit A / (m/s), where g is the voltage constant of the piezoelectric material, with unit (V/m) / Pa, and C is the capacitance of the PZT device. The reflector and adaptor specific impedances are denoted as Z_R and Z_A respectively. The pipe can be modelled as a T network. A detailed analysis of modelling of PZT devices using the Mason and the KLM equivalent circuits can be found in [12, 13].

4. Experimental results

To evaluate the feasibility of the proposed concept, an experimental system was constructed. A schematic of the setup is shown in Fig. 2 (left). Two identical transducers are used as the transmitter and the receiver, each consisting of an APC International Ltd PZT 850 disk with diameter 48 mm and thickness 7.9 mm, a $60 \times 60 \times 20$ mm aluminium reflector on top and an aluminium adaptor of the same size with a concave side on the bottom. The density, dielectric and voltage constants of the PZT 850 material are 7600 kg/m^3, 1900 and 26.8 mV/m respectively [14]. The two transducers were mounted on a 1.8 m long, Ø 118 mm cast iron pipe, with 8 mm wall thickness, at various distances, using adjustable straps (red in Fig. 2, right).

The electrical impedance of the PZT disk was characterized by I-V measurements, using a 10 V amplitude signal in the range between 1 kHz and 1 MHz. The current was monitored through the voltage drop on a 50 Ω resistance connected in series with the transducer. The response of an un-mounted PZT disk is presented in Fig. 3 (left). Characteristic resonance-anti-resonance peaks that correspond to vibration resonance, expressed by the tangential terms in the Mason model, are observed at various frequencies. In order to identify their origin, the calculated impedance of the PZT is also plotted for comparison, for axial and radial vibration. For this calculation, the model outlined in Section 3 was used, using the nominal values of the PZT devices, with a sound speed of 4600 m/s and a corresponding bulk modulus of 168 GPa. The un-mounted PZT device corresponds to zero forces at its surfaces, and hence short-circuited terminals in the Mason model. The comparison illustrates that the lower frequency resonances correspond to the radial vibration modes of the disk, with τ = 46 mm, corresponding to 196 kHz, while the larger frequency resonance, corresponds to the axial mode, with τ =7.9 mm, corresponding to 1.19 MHz. For reference, the case of a hardbound PZT, such that no lattice motion is possible at the edges is also plotted in Fig. 3 (left). This corresponds to open circuit conditions in the Mason model, giving an impedance of 1/ωC.

The effect of mounting on the electrical impedance of the PZT disk is studied in Fig. 3 (right), where the responses of an un-mounted disk, a disk attached to the reflector and adaptor parts, and a pipe-mounted disk (shown in Fig. 3, right) are compared. As expected, the additional impedance induced by the aluminium brackets reduces the intensity of the PZT disk resonance effects. This serves as an indication of power delivery to the pipe and can be used as a measure of mounting quality, or to identify a successful device mounting during the installation of transmitter and receiver devices.
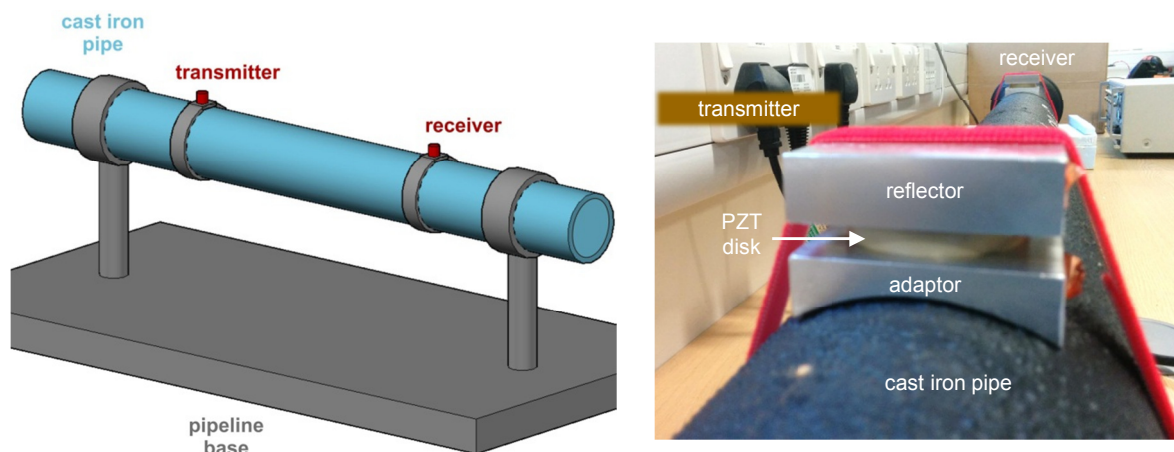

Figure 2: Schematic (left) and image (right) of the acoustic power transmission evaluation setup.
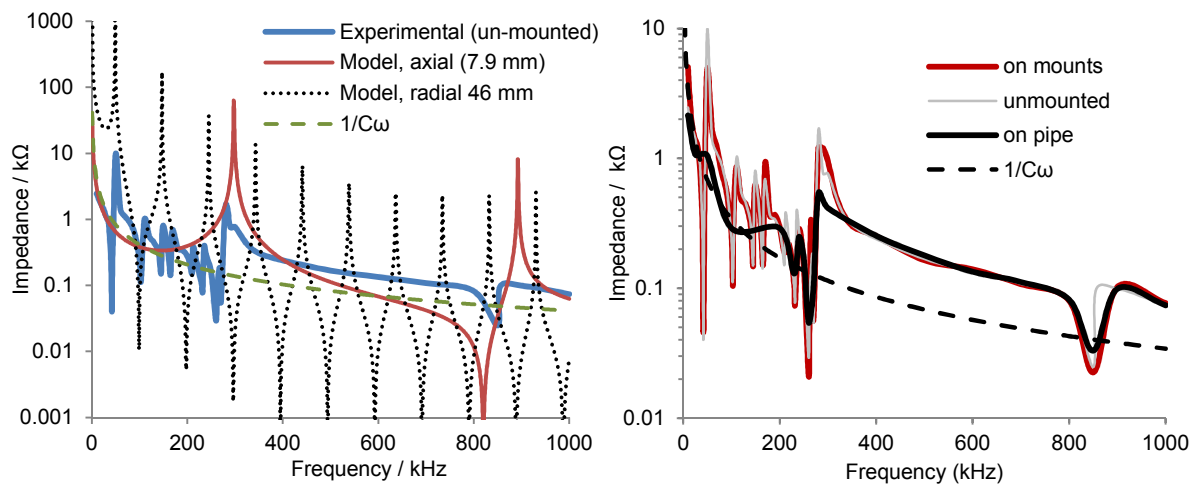
Figure 3: Left: Calculated and measured electrical response of the PZT transducer without mounting. Right: Measured electrical response in different mounting states.

Power transfer experiments were carried out using a function generator in the 1 kHz – 100 kHz frequency range, with a Falco WMA-300 high voltage amplifier to drive the transmitter PZT disk, with voltage amplitude up to 150 V. The distance between the transmitter and the detector was 1 m. A resistive load R_L was connected directly to the receiver PZT output. The optimum R_L value depends on the operation frequency. The level of received power is also frequency dependent. In the particular set up used, peak received power was observed at 48.5 kHz, with R_L = 1.5 kΩ. This is demonstrated in the measured transmitted and received signals shown in Fig. 4 (left). The transmission signal is a 150 V, 48.5 kHz sinusoidal signal, pulse-modulated at a frequency of 200 Hz and 25% duty cycle. The amplitude of the sinusoidal voltage amplitude measured on R_L was 1 V, corresponding to a received RMS power of 0.33 mW for a continuous drive signal.

The received voltage was measured as a function of the applied voltage amplitude at the transmitter. The results are shown in Fig. 4, right, both for the open-circuit voltage, and the 1.5 kΩ load. A linear relationship between input and output is observed, at good approximation, with a gradient of 2.5 mV/V. The ratio of output voltage on R_L to the open circuit voltage remains constant in the transmission voltage range between 50 V and 150 V, at around 55%. The corresponding power delivery range that is demonstrated in this experiment is between 20 μW and 100 μW. This is less than the 0.33 mW demonstrated in the experiment of Fig. 4, left, because during the voltage sweep, emphasis was given to consistency of mounting conditions rather than to achieving maximum power. In practice, the 0.33 mW output was demonstrated by pressing down the receiver to achieve better contact. In voltage sweep, this was avoided for consistency. This power delivery level is adequate for the requirements of low power sensor nodes and the corresponding voltage is sufficient to drive commercial power management systems designed for energy harvesting devices.

6. Conclusion

In this paper, a new method for remote powering of sensor nodes installed on structures such as metal pipes was proposed. A simple theoretical analysis framework was drawn and an experimental validation setup was designed and built. Acoustic delivery of 0.33 mW RMS power through a pipeline at a distance of 1 m was demonstrated. This power range may be adequate for various application scenarios, such as corrosion monitoring of pipeline networks, where the data acquisition scheduling permits duty cycled node operation. Optimization of the acoustic mode selection, transmitter and detector designs, and practical mounting, are expected to enable a practical solution to the challenge of powering sensor nodes that are permanently installed in remote locations.
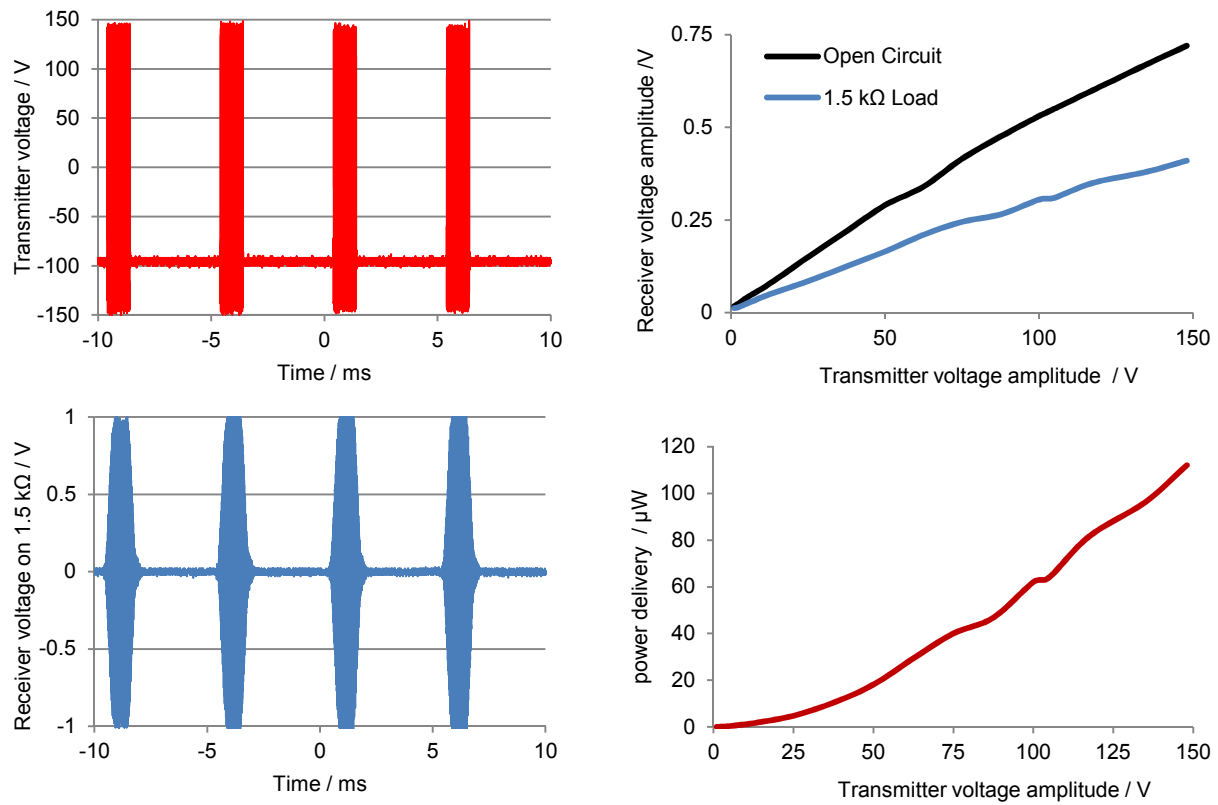
Figure 4. Left: Transmitter and receiver voltage at 48.5 kHz, at a distance of 1 m, demonstrating a received power of 0.33 mW. The transmission is pulsed to show the acoustic delay between the signals. Right: Received vs transmitted voltage (top) and corresponding delivered power (bottom) at 48.5 kHz, at a distance of 1 m.

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