System for detection and prediction of the phenomenon of brittleness in the natural gas transmission network combined with hydrogen

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1 Introduction

The European Union aims to use the Natural Gas infrastructure (gas pipelines) for the transport of Hydrogen (a mixture of natural gas and hydrogen). The problem arises in that the steel with which these pipelines are made is affected by the phenomenon of "hydrogen embrittlement" (HE).

Hydrogen embrittlement (HE) is the loss of ductility of a metal and reduction of load-bearing capacity due to the absorption of hydrogen atoms or molecules by the metal. At the molecular level, hydrogen ions are introduced between the granular boundaries of the steel where they recombine into molecular hydrogen, occupying more space and weakening the bonds between grains. The result of HE is that the components crack and fracture at stresses below the yield strength of the metal. In the case of the transport of the NG and Hydrogen mixture, Hydrogen penetrates by diffusion into the steel due to the service conditions (pressure and flow) in which it is found. A detailed description of the hydrogen embrittlement process can be found in [1].

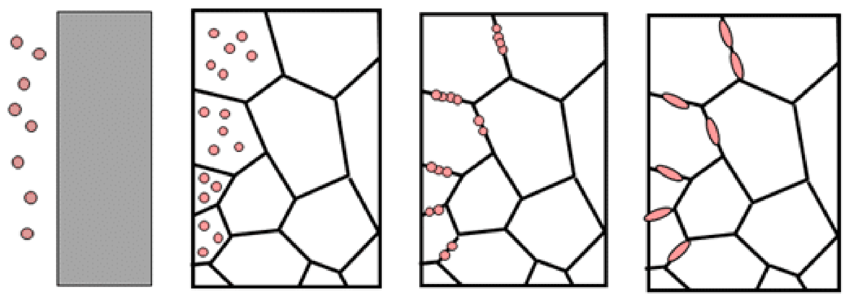

Figure 1. Scheme of the effect of Hydrogen brittleness. Source: [1]

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From the analysis of 372 hydrogen-related accidents in [2] from the ARIA database (France), 27% involved hydrogen-induced leaks or stresses in materials.

There are different HE prevention techniques, including:

- Using the infrastructure without modifications with preventive monitoring.
- Using HE inhibitors
- Applying HE-resistant internal coatings
- Installing HE-resistant piping inside

In this work we propose as the optimal solution the technique of using the infrastructure without modifications by performing a preventive monitoring of HE. Specifically, the general objetive of this project is to develop a novel system for the management of the combined transport of Natural Gas and Hydrogen, capable of:

- Detect the degree of Hydrogen embrittlement of the steel pipelines used for Natural Gas transport in real time and continuously.
- Manage the Hydrogen transport in order to limit the Hydrogen concentration in the steel.

2 Methods

The system is based on the electromechanical impedance (EMI) technique, which employs PZT sensors to monitor variations in the dynamic characteristics of the structure (mass, damping and/or stiffness).

The EMI technique is used in all types of structural analysis such as corrosion detection in [3] or aircraft structural health in [4].

The system presented is based on the relationship between the elastic modulus (which decreases due to the effects of HE, this relationship is detailed in [5]) and the natural frequencies of vibration in the pipe, since these decrease as the elastic modulus decreases, as demonstrated in [6].

PZT sensors act simultaneously as an actuator (deforming when a strain is applied) and as a strain sensor (generating an electric potential when deforming). Thus, the EMI technique procedure is summarized in the measurement of the impedance in a resonance frequency.

$$f_{\mathrm{N}} = K \cdot \sqrt{E}$$

$$Where\ K\ depends\ of\ geometry$$

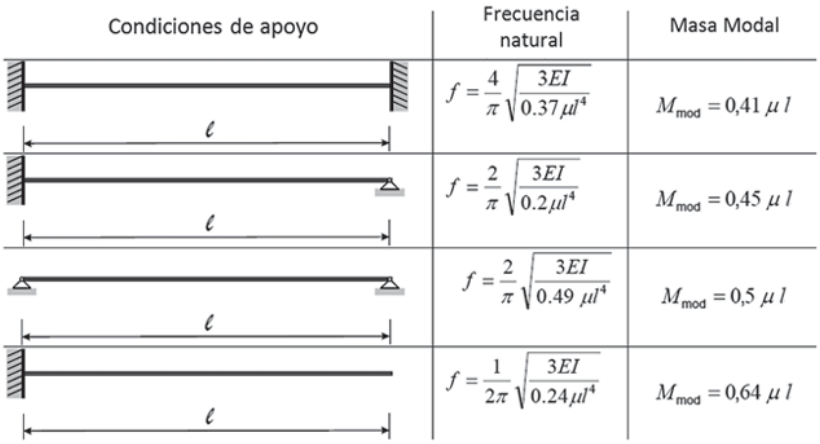


Figure 2. Relation between resonance frequency and elastic modulus [5]

2.1 Electromechanical impedance

Electromechanical impedance is a structural monitoring method that uses piezoelectric transducers, relating the mechanical impedance of the evaluated structure with the electrical impedance measured in the transducers, so that the mechanical resonance spectrum of the structure is reflected in an almost identical spectrum of the real part of the electromechanical impedance measured in the piezoelectric transducers.

Thus, the electromechanical coupling is exploited, associating the electrical response of the piezoelectric transducer with the mechanical impedance of the evaluated structure, allowing an indirect measurement of the changes in the mechanical impedance of the structure, circumventing the difficulties to perform a direct measurement of this variable, which provides information of the structural properties of the mechanical system. A more extensive description can be found in [7].

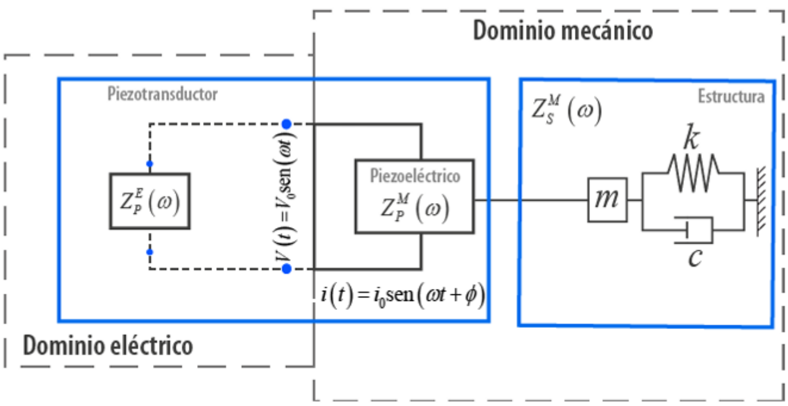


Figure 3. Electrical diagram equivalent to the electromechanical coupling. Source: [7]

2.2 Frequency analysis of the EMI technique for the detection of fragility

The EMI technique consists of measuring the impedance of the piezoelectric material on the structure. It requires the measurement of the electrical impedance Z = R + X-j (R = real part; X = imaginary part) in a frequency range from 10 kHz to 150 kHz.

The impedance measurement technique is based on the discrete Fourier transform (DFT).

$$Z(f_0) = \left.\frac{V(f_0)}{I(f_0)}\right|_{f=f0}$$

Where:

$$V(f) = fft(v(t))$$

$$I(f) = fft(i(t))$$

$$f_0 = frecuency\ source$$

However, the Fourier transform requires a high computational calculation. For DFT, $4 \cdot N^2$ multiplication operations are required, while for FFT (approximation) $2 \cdot N \cdot \log_2 N$ operations are required. However, this is still a large number of operations for the acquisition frequencies required.

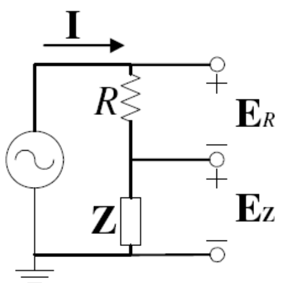


Figure 4. Impedance measurement circuit. Source: [8]

$$V(t) = V_{max}\cos(\omega t + \alpha)$$

$$V(t) = e_R(t) + e_Z(t)$$

$$e_R(t) = \frac{R}{|R+Z|} U_{max}\cos(\omega t + \alpha - \gamma)$$

$$e_Z(t) = \frac{|Z|}{|R+Z|} U_{max}\cos(\omega t + \alpha - \gamma + \Phi)$$

Where:

$$f_s = \frac{1}{T_s} = \frac{N\omega}{2\pi} = \frac{N \cdot 2\pi f_0}{2\pi} = N \cdot f_0$$

In order to reduce the computational cost of data processing, the following expressions developed in [8] are used.

$$e_R(nT_s) = \frac{R}{|R+Z|} U_{max} \cos\left(\frac{2\pi}{N}n + \omega t_0 + \alpha - \gamma\right)$$

$$e_Z(nT_s) = \frac{|Z|}{|R+Z|} U_{max} \cos\left(\frac{2\pi}{N}n + \omega t_0 + \alpha - \gamma + \Phi\right)$$

$$\left.\begin{aligned} a_R &= \frac{2}{N}\sum_{n=0}^{N-1} e_R(nT_s)\cdot cos\left(\frac{2\pi}{N}n\right) \\ b_R &= \frac{2}{N}\sum_{n=0}^{N-1} e_R(nT_s)\cdot sin\left(\frac{2\pi}{N}n\right) \\ a_Z &= \frac{2}{N}\sum_{n=0}^{N-1} e_Z(nT_s)\cdot cos\left(\frac{2\pi}{N}n\right) \\ b_Z &= \frac{2}{N}\sum_{n=0}^{N-1} e_Z(nT_s)\cdot sin\left(\frac{2\pi}{N}n\right) \end{aligned}\right\} \rightarrow \begin{aligned} |Z| &= \frac{\sqrt{a_Z^2 + b_Z^2}}{\sqrt{a_R^2 + b_R^2}}\cdot R \\ \emptyset &= tan^{-1}\left(\frac{a_z b_R - a_R b_Z}{a_z a_R + b_z b_R}\right) \end{aligned}$$

Through these simplifications they are reduced to 4·N + 8 multiplication operations.

2.3 Development of measurement system

The preliminary design of the measurement node is shown below.

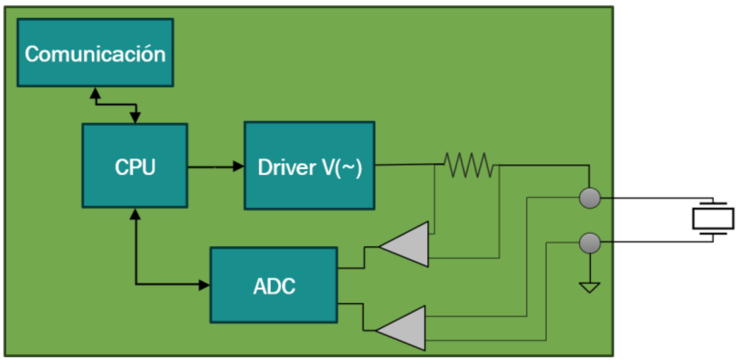


Figura 1. Hardware system scheme. Source: self-made.

- CPU: STM32H743VT6
- Driver V(~): Internal DAC H7
- ADC: AD4001

- Communication system: u-blox SARA-R410M
- Power supply: solar system (MPPT LT3652 + 2cell LiFePO4)

PCB design

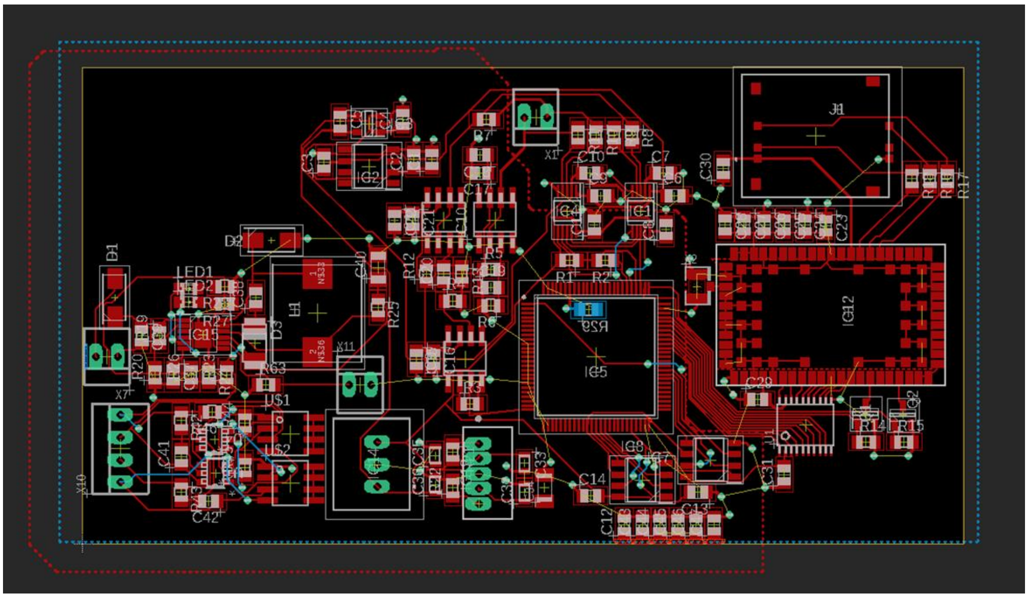


Figure 5. Printed circuit of the HITARY system. Source: self made...

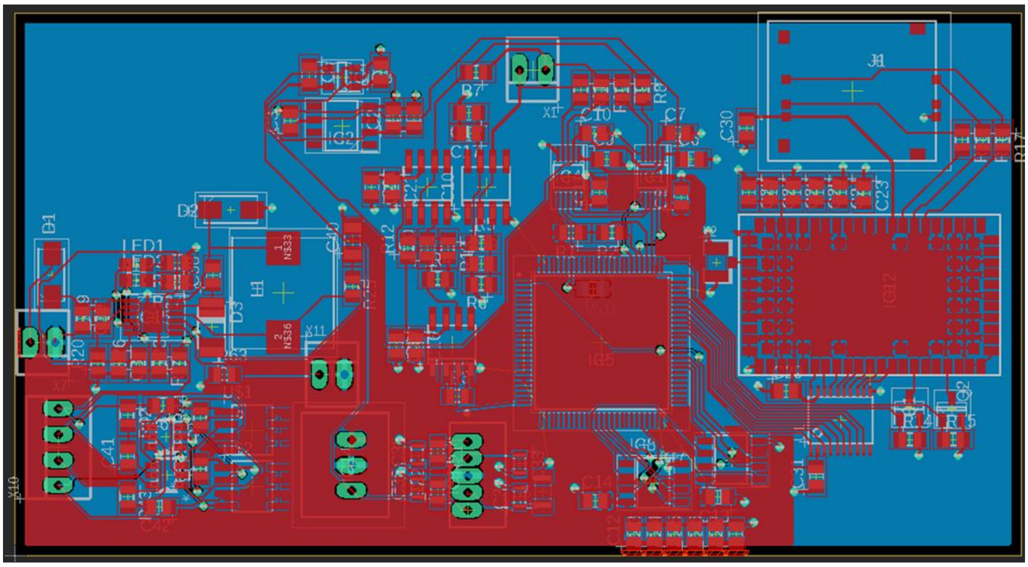
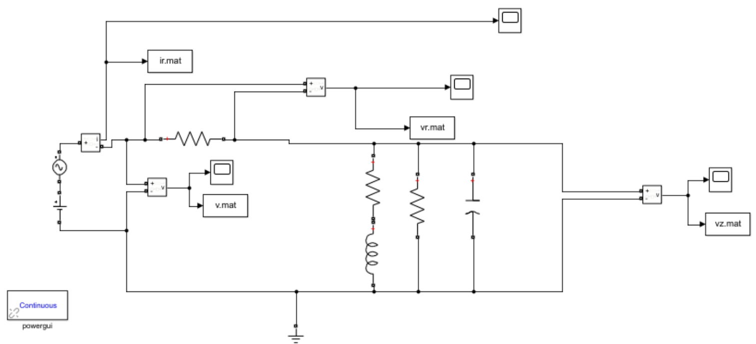


Figura 2. Printed circuit of the HITARY system. Source: self made.,TOP and BOTTOM layers. Source: self made

3 Results

To evaluate that the system measures the impedance correctly, an experimental circuit has been built using passive elements (resistors, capacitors, and inductors). From the circuit we have compared the theoretical curves with the curves obtained experimentally by the system:



Where:

- fs = 1 MHz
- Vexc = 10 Vp
- Fexc = 1 – 100.000 Hz
- Rshunt = 400 Ohms

Figure 6. RLC circuit for impedance measurement. Source: self-made.

The results obtained using the device (left) and those obtained using the Impedance Measurement module of Simulink (right) can be seen below.

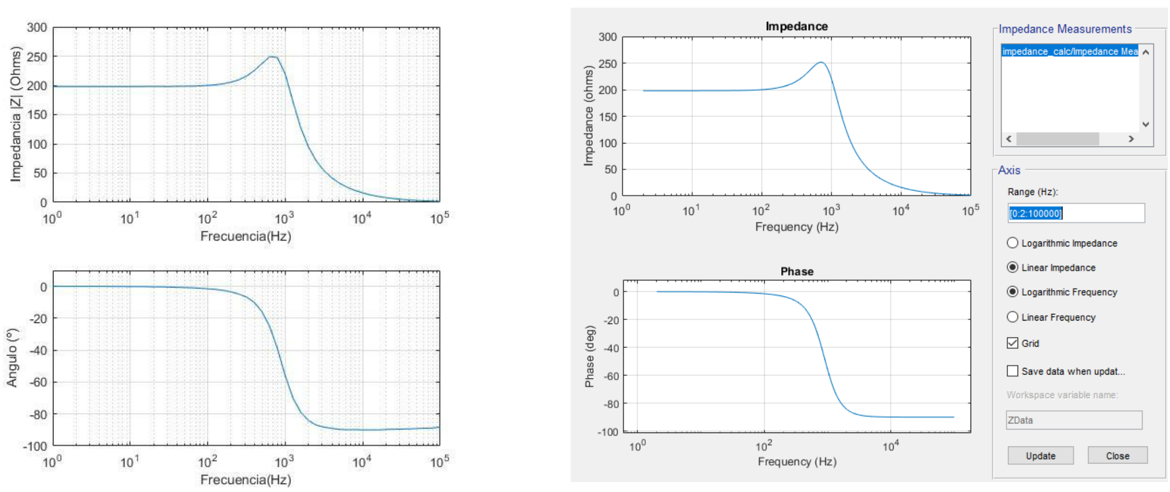


Figure 7. Comparison of theoretical results and experimental of Z and Φ. Source: self-made

As can be seen in the above plots the results of the impedance modulus (Z) and phase (Φ) coincide with an error of less than 2%.

4 Conclusions

- The degree of hydrogen embrittlement affects the elastic modulus of the material. Even in advanced stages, it can lead to brittle fracture.
- Variations of the elastic modulus directly influence the resonance frequencies of the construction element.
- The most standardized method for measuring resonance frequencies is based on the measurement of electromagnetic impedance by means of a piezoelectric element.
- A system capable of measuring the electrical impedance of a piezoelectric sensor attached to the surface of the building element has been developed.
- The developed system has the necessary components, a controller, a long-distance communication system and a power supply system based on a solar system, to be installed along a natural gas transport network.
- The system allows a real time monitoring of a natural gas transport network.

References

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