Implementation of an ultrasonic tomograph for small specimens

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Abstract. The implementation of an open freeware to acquire and reconstruct ultrasonic images from tomographic projections is presented. This proposed tomograph consists of three main modules: the mechanical position system, control system and the ultrasonic pulse emission-reception system. The communication, synchronization among these modules, experimental parameters and image reconstruction are done by an interface based on JAVA. The preliminary results show that the system is able to produce quality images of tested specimens.

1. Introduction
There are many techniques to characterize the degradation process in cement structures. Among these, ultrasonic non-destructive testing has a great importance since it allows mechanical and physical properties characterization of the structures without altering their integrity [1]. Also this methodology is relatively easy to perform, is of low-cost, and provides information about the physical properties of the studied material [2], however, despite all these advantages, ultrasonic tomography had presented little development [3] and practically have not been applied for monitoring cement based materials [4,5]. In this work we developed an ultrasonic tomographic system that allows us to obtain projections for samples of different materials and shapes, also we present the algebraic reconstruction method (ART) to generate the images from the signals captured as a first approximation of this study.

1.1. Ultrasonic Tomograph Prototype
The proposed tomograph basically consists of three main modules: the positioning system (PS), the control system (CS) and the ultrasonic pulse emission-reception system (ERS). The PS is responsible for generating the movement of the ultrasonic transducers to have the projections of the object under study. The system is composed of mechanical system and an electronic control system. The mechanical system consists of: transmission shafts, bearings, gears and pinions. The electronic system by: microprocessor and a power supply (ATmega328P and driver bridge L298N). The scan is circular (with a diameter of 30 cm) and the movement is carried out by means of two concentric axes, which are attached two arms that hold each transducer. The transmission system is formed by a pair of gears that transmit the movement of the motor to the axes, the pinion connected to a step motor (National Instruments, NEMA 17-42BYGHM810) has a diameter of 4cm (20 teeth), and the Shaft gear has a diameter of 8cm (40 teeth). The ERS was implemented with the HandyScope HS3⁵ that is responsible of generating and receiving
the ultrasonic beams. The Handyscope HS3\textsuperscript{(R)} has a 50 MS/s sampling clock, a 256K samples deep waveform memory, a 14-bits output resolution and a $\pm 12$ V output range. The function generator was programmed to design excitation pulses, where the user can vary the type of wave (square, sinc, etc.), amplitude and the sampling frequency. And the oscilloscope is in charge of acquiring and amplified the signal from the receiver. The CS controls the signal generator, the oscilloscope and the movement of the motors, it works through an interface programmed in Java language, this for the portability of the program and its compatibility with different computational environments. Also CS is responsible of the communication between PS and ERS, and their synchronization. The system moves the motors by sending a signal to the microcontroller and after 3 s (to assure the stability of position system), a message to the ERS is sent to generate the ultrasonic signal and acquire 100 signals coming from the specimen at the same position of the transmitter and receiver transducers. After that the PS moves the motors to the next position. This process is done iteratively until 360\degree are covered. Figure 1 sketches a stage diagram of the ultrasonic tomograph and a photograph of the prototype is in Figure 2.

1.2. Tomographic reconstruction

The mathematical basis for the reconstruction of tomographic images for non-diffractive sources was formulated by Johann Radon in 1917 \cite{6}, the formulation is based on the line integral and is able to recover the cross section of an object from the data of projection. The Radon transform applied to an image $f(x,y)$ can be written as.

$$R(\rho, \theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y) \delta(\rho - x \cos \theta - y \sin \theta) \, dx \, dy \quad (1)$$

where $\delta(\cdot)$ is the Dirac delta function, $\rho$ is perpendicular distance between the origin to the line given by $\theta$ orientation. For each direction a projections of the image along specific path is computed which consists of the sum of the pixel intensities. To solve the inverse problem, the inverse Radon transform recovers the original image. However this methodology is based on continuous information. Therefore, to reconstruct images from discrete projection, given by tomographic experimental setup then the transform must be discretized by algebraic methods \cite{7}.

Algebraic methods assume that there is a mesh on the object image to be reconstructed, it must also assume that the values of the image are constant within each cell of the mesh (pixel).
The projections of a beam tomography parallel to a $\theta$ angle are shown in Figure 3, where $\tau$ represents the positions of the transducers and $p_m$ the projections in the different positions of the transducers. As it can be seen, the beam of each transducer intercepts each cell of the mesh completely or partially, so a weight function must be established to get the percentage of the total cell area within the beam.

![Figure 3. Mesh and ultrasonic beams width at $\theta_0$ [8].](image)

![Figure 4. Iterative solution for a 2D space and its linear equation system.](image)

It is possible to write the relation between the image of the object, the projections, and the weights ($A_{mn}$) by means of a linear system:

\[
\begin{align*}
A_{11} \cdot X_1 + A_{12} \cdot X_2 + A_{13} \cdot X_3 + \cdots + A_{1N} \cdot X_N &= p_1 \\
A_{21} \cdot X_1 + A_{22} \cdot X_2 + A_{23} \cdot X_3 + \cdots + A_{2N} \cdot X_N &= p_2 \\
A_{M1} \cdot X_1 + A_{M2} \cdot X_2 + A_{M3} \cdot X_3 + \cdots + A_{MN} \cdot X_N &= P_M
\end{align*}
\]

In this formulation each equation represents a beam and the projections $P_M$ are the result of the sum of the product of each weight with the value of the image in each cell $X_N$:

\[
P_M = \sum_{n=1}^{N} A_{MN} \cdot X_N
\]

(3)

It is possible to write the system in matrix form, where $X$ represents the image, $p$ is the vector of projections and $A$ is the weight matrix [9].

\[
p = A \cdot X
\]

(4)

The tomographic reconstruction consists of solving this system of eq. (3), determining the image $f$ from the projections $p$, the most common and simple method to solve this type of system is known as the projection method. It was described by the first time by Kaczmarz [10,11]. It can be understood geometrically as a set of hyper planes of dimension $M^2 - 1$ within the $M \times M$ space of the images. The solution of the system will be a common point to all these hyperplanes; that is, a point that satisfies the equations. A method to arrive at the intersection point of several hyperplanes starting from an arbitrary starting point is to orthogonally project the point on the first hyperplane, the point found is projected onto the second hyperplane and so on. When it has been projected on the last hyperplane, it is projected again on the first and the
process is continued. To graphically represent the process, lines are shown in two dimensions in the Figure 4 where the first number between parentheses represents the iteration and the second one identifies the line. If the system has a solution, convergence is assured, even when the convergence rate depends on large order of the hyperplanes. The investment of the eq. (4) can be written as [9]:

\[ X_1^{(k)(j)} = X_1^{(k)(j+1)} + [A_{ji} \cdot \left( p_j - \sum_{l=1}^{M \times M} A_{jl} \cdot X_1^{(k)(j-1)} \right)] \left( \sum_{l=1}^{M \times M} A_{jl}^2 \right)^{-1} \] (5)

where \( X^{(k)(j)} \) is the reconstructed image based on the previous reconstruction, \( A_{ji} \) are weights and \( p_j \) the projections.

2. Results and discussion

Two cylindrical specimens of 5 cm in diameter and 10 centimeters in height were used, ones is a aluminium probe and the other is a cement paste at 0.3 w/c ratio. The experimental projections were taken under the following parameters: the motor step was 3.6 degrees, two Olympus\textsuperscript{(R)} ultrasonic unfocused immersion transducers of 1.9 cm in diameter with 1 MHz operating frequency, one to generate the ultrasonic pulse and the other to receive the ultrasound signal. For each position 100 signals were acquired at a rate of 12.5 MHz and averaged. The ultrasonic pulse was excited with a design sinc function and 10 V amplitude. Figure 5 shows a set signals obtained from the aluminium specimen, where each row corresponds to an ultrasonic beam at specific direction. The image show two vertical in phase pulses, where the diameter of the probe can be calculated since the attenuation of the media is very low. On the other hand a different behavior is shown in Figure 6, where the cement paste is highly attenuating and dispersive. Reconstruction images of the probes are shown in Figures 7 and 8 using eq. (2). In both cases the probe shape is reconstructed but for the cement probe the image is very noisy and the contour is not well defined as the aluminium case.

![Figure 5. Signals obtained by the tomograph for a specimen of aluminium](image1)

![Figure 6. Signals obtained by the tomograph for a specimen of cement paste with water/cement ratio 0.3](image2)

3. Conclusions

The designed tomographic system has a freeware interface based on JAVA giving the flexibility to work on Windows or Linux platforms. This open system allows the configuration of the mechanical system, where it could be programmed to acquired data along circular path, in radial and fan modes, several resolution motor steps. Also several ultrasonic parameters can be configured such as the pulse width, amplitude, number of samples, sampling frequency and the pulse excitation shape.

The data used for the reconstruction algorithms were the result of averaging 100 signals at each position in order to achieved a high signal to noise ratio. The reconstruction of the data was
computed using a very simple algebraic algorithm for the discretization process and Kaczmarz method for solving the linear equation systems. The resulting tomographic images allow to measure the objects size and shape, however due to mathematical noise the internal structure of the heterogenous specimen is lost. Therefore a further research about reconstruction algorithms for dispersive media must be carried out.

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