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Numerical Simulations of Ultrasonic Non Destructive Techniques of Masonry Buildings.

B. Cannas[1], S. Carcangiu [*,1] G. Concu[2], A. Fanni[1] and M. Usai [1]
[1] Department of Electric and Electronic Engineering, University of Cagliari, Piazza d'Armi, 09123 Cagliari, Italy
[2]Department of Structural and Infrastructural Engineering and Geomatics, Piazza d'Armi, 09123 Cagliari, Italy
*Corresponding author: Piazza d'Armi, 09123 Cagliari, Italy; s.carcangiu@diee.unica.it

Abstract: An experimental program has been developed, with the purpose of evaluating the reliability in building diagnosis and characterization of an integrated analysis of several parameters related to several acoustic parameters, associated with acoustic waves propagating through the material. The Direct Transmission Technique has been applied. In this paper we developed a numerical model, with the Finite Element Method, using the Transient Acoustics-Piezoelectric Interaction application mode of COMSOL. The analysis has been carried out on a model of trachite stone masonry with an inside cavity. The time travels associated with acoustic waves propagating through some sections of the considered models have been analyzed to tune COMSOL applications in order to detect the presence of the central cavity. The comparison of the obtained results with those supplied by experimental tests has been performed.

Keywords: Ultrasonic wave, Non-Destructive Testing, signal processing, Acoustic analysis, Piezoelectric transducer.

1. Introduction

Building preservation and restoration is a complex problem to deal with, especially when concerning building of historical relevance. The evaluation of a structure real state shouldn't interfere with the condition and the functionality of the building, and should possibly involve limited costs. Thus, inspection and monitoring of structural conditions is becoming an essential part of proper management of buildings rehabilitation.

In the field of assessment methodologies, particular importance is given to developments of Non-Destructive Techniques (NDTs), including automated procedures and information technology to support decision making and evaluation of data. NDTs aspire to achieve the higher number of information about materials and structures without altering their condition, for example by extracting samples. Thus, the ageing of building heritage and the need of guarantee its safety, especially when reconstruction of its past life and previous restorations is not clear, has led to the creation, the evolution and the rapid diffusion of those type of methodologies, in order to proper manage buildings rehabilitation. In fact, every work must be preceded by careful observation of the effective state of the building so as to ascertain the nature of possible structural inadequacies and be able to proceed with works that are suitable and sufficient for the rehabilitation of the building and its characteristics.

An experimental program has been started with the purpose of evaluating the reliability in masonry diagnosis and characterization of the integrated analysis of several parameters associated with acoustic waves propagating through the material. Experimental tests are based on ultrasonic techniques.

In this paper the finite element method is applied to the problem of non destructive testing.

This is one possible way to visualize the real acoustic wave propagation into the structure. The present work has an objective to obtain a reliable numerical model of generation and reception of the ultrasonic waves through piezoelectric transducers, using the finite element method.

To validate the model, experimental measurements were carried out using the equipment PUNDIT **(P**ortable **U**ltrasonic **N**ondestructive **D**igital **I**ndicating **T**ester), manufactured by CNS Farnell of London [1]. PUNDIT allows online data acquisition, waveform analysis and full remote control of all transmission parameters. Furthermore, his measuring device has the advantage of providing to emitter transducer a signal high enough not to necessitate the use of an amplifier. The emitter and receiver are transducers that consist of lead zirconate titanate (PTZ4) ceramic piezo electric elements in stainless steel cases with a natural frequency of 54 kHz. The emitter is connected to the signal generator of the PUNDIT equipment. Both transducers are connected to a digital oscilloscope Agilent DP03000.

2. Ultrasonic Techniques

Among the different non destructive diagnostic methods, Ultrasonic Techniques (UT) seem to be very suitable for evaluating a buildings condition, because they give information with immediacy, rapidity and relatively low cost. Ultrasonic analysis of materials is based on the principle that the propagation of any wave is affected by the medium through which it travels [2, 3]. Thus, changes in measurable parameters associated with the passage of a wave through a material can be correlated with changes in physical properties of the material [4].

UT traditional application is based on measurements of the velocity $\boldsymbol{v}$ of waves propagating through the material, that is the easier and faster way to get relevant information from the wave. In fact, the operative procedure to acquire waves velocity and to process data in order to get immediate results is quite simple: $\boldsymbol{v}$ is obtained from the ratio $\boldsymbol{l/t}$, where $\boldsymbol{t}$ (propagation time) is the time wave needs to travel along the path of length $\boldsymbol{l}$. This allows to obtain the average velocity related to the wave path crossing the object thickness. Moreover, the skills of this parameter are very useful. In fact, from wave's propagation theory it is known that $\boldsymbol{v}$ is dependent on the following material's characteristics: dynamic elastic modulus $\mathbf{E_d}$, Poisson's number υ and density ρ. For an homogeneous isotropic material this function is:

$$v = \sqrt{\frac{E_d(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad (1)$$

Thus, $\boldsymbol{v}$ is directly related to structure elastic parameters, crucial for determining structure health and lastingness, so that it has been frequently applied for evaluating structures integrity and restoration's effectiveness [5].

UT are preferentially carried out applying the Direct Transmission Technique (DTT), in which the wave is transmitted by a transducer (Emitter) through the test object and received by a second transducer (Receiver) exactly on the opposite side. The DTT is very effective, since the broad direction of waves propagation is perpendicular to the source surface and the signal travels through the entire thickness of the item. Standards concerning the determination of waves velocity in structures [6] suggest, therefore, the application of this kind of signals transmission.

The propagation velocity, although is a significant parameter, limits the investigation at the analysis of propagation times, not taking into consideration important information regarding the way the waves are propagating. For instance, when a wave passing through a specific item encounters any discontinuity, the wave power is certainly attenuated because of scattering phenomena, while the propagation time may not be moved if part of the signal is already able to reach the receiver. Therefore, it would be reasonable to approach the ultrasonic analysis also in terms of other wave's features changes and not only in terms of propagation times. The higher the intrinsic non-homogeneity level of structures, e.g. masonries, the grater the advisability of this integrated approach.

In fact, as documented by various studies [7, 8], predominantly performed in the geophysics and aeronautics environments, other wave's characteristics such as attenuation, scattering and frequency content, primarily related to the elastic wave power, may allow one to get more and relevant information about the material, because of the reliance of the propagation on the properties of the medium through which waves travel. In fact, different materials absorb or attenuate the wave power at different rates, depending on complex interactive effects of material characteristics, such as density, viscosity, homogeneity. Additionally, waves are reflected by boundaries between dissimilar materials, so that changes in materials structure, e.g. presence of discontinuities or defects, can affect amplitude, direction, and frequency content of scattered signals. Furthermore, all materials behave somehow as low pass filters, attenuating or scattering the higher frequency components of a broadband wave more than the lower. Thus, waves analysis in both time and frequency domains can give information on the combined effects of attenuation and scattering as previously described.

3. Case study: geometry and mesh

The analysis has been carried out on a trachite stone masonry with an inside cavity. The wall is 90 cm wide, 62 cm high and 38 cm thick, and it is made of trachite blocks sized

$20 \times 38 \times 12$ cm^3, settled as shown in Fig. 1-2 and jointed with cement lime mortar. The block assigned to the central position of the wall was not settled, thus realizing a macro-cavity with the same size of the missing block (Fig. 2), and assumed as a known anomaly. Mortar joints have been assumed to be 1 cm thick, but since the wall was manually built by a builder, actual dimensions are not so precise.

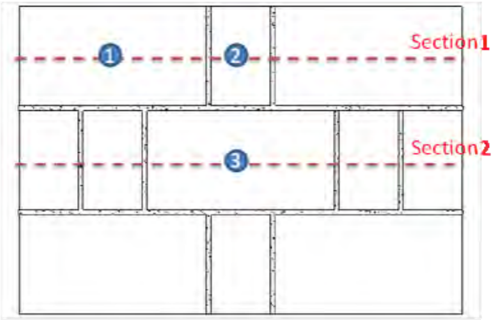

Figure 1. Front view of the wall.

By the DTT, the ultrasonic wave is transmitted through the wall and received by a second transducer on the opposite side of the structure. Changes in received signal provide indications of variations in material continuity. In this case study, 3 emitters and 3 receivers have been arranged in opposite surfaces of the wall, as shown in Fig. 1.

In this work a simplified COMSOL model to study the acoustic wave propagation through materials with different acoustic properties is presented. As can be noted in Fig. 2, the transmission is characterized by different paths of the ultrasonic wave through the wall:

- path 1: trachite-cement lime mortar,
- path 2: trachite,
- path 3: trachite–air.

Firstly, we have calibrated the model considering a reference bar of aluminum supplied with PUNDIT equipment that has a transmission time of typically 24 μs. The aluminum bar sized 153x50 mm, the transmitter and receiver transducers and the meshed geometry model are shown in Fig. 3.

In order to resolve the wave equally well in time as the mesh does in space, an opportune element size l_e of the mesh has been chosen. In fact, any longer time steps will not make optimal use of the mesh, and any shorter time steps will lead to longer solution times with no considerable improvements to the results.

The time step and mesh size were carefully chosen to obtain a proper number of nodes per wavelength. The relationship between mesh size and time step is known as the Courant–Friedricks–Lewy (*CFL*) number condition [9]:

$$CFL = \frac{c \cdot \Delta t}{l_e} \qquad (2).$$

where c is the speed of sound, Δt is the time step and l_e is the mesh size.

Considering a *CFL* number of 0.025 that proves to be near optimal, a maximum element size equal to 0.01 m has been set.

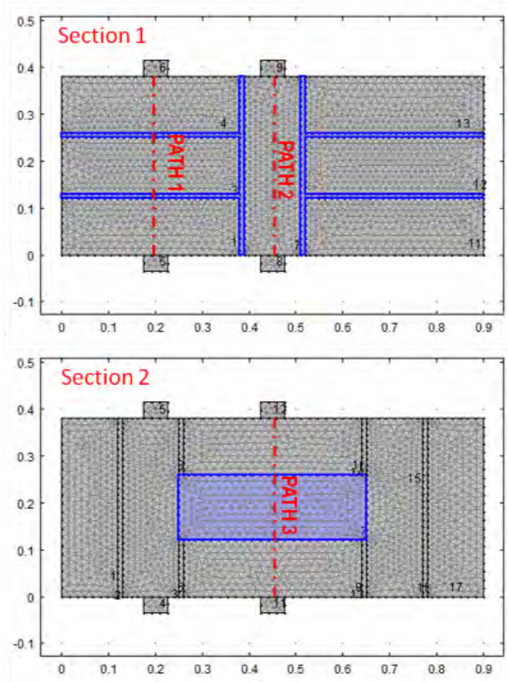

Figure 2. Meshed model of the horizontal plane sections with the indication of different paths of transmission.

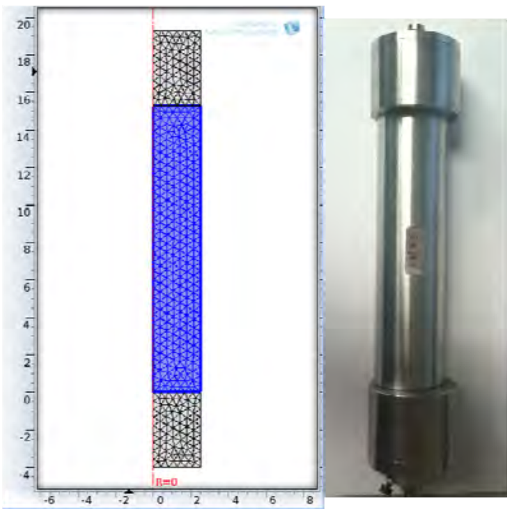

Figure 3. Transducers and reference bar of aluminum: meshed model and PUNDIT equipment

4. Governing Equations and boundary conditions

All the analysis have been carried out using the *Transient Acoustics-Piezoelectric Interaction* application mode, belonging to the COMSOL Acoustics Module. An axial symmetric geometry has been considered in order to reduce the computational time of simulations performing a transient analysis with a time dependent solver. In this way a vibration of the first electrically charged piezoelectric material (the emitter) is applied to the bar or to the wall and the acoustic wave propagating into the different materials arrive at the second piezoelectric material (the receiver) that produces an electric current from the acoustic field. Each material is characterized by its own density, Poisson ratio, Young's modulus and sound speed as shown in Table 1.

Table 1: Materials properties

	Aluminum	**Trachite**	**Mortar**
Poisson's ratio	0.33	0.2	0.1
Young's modulus [MPa]	70e9	6.1e9	5.5e9
Velocity of sound [m/s]	6375	1968	1768
Density [Kg/m^3]	2700	1750	1800

The acoustic pressure $p(\mathbf{r},t)$ in a medium is governed by the following partial differential equation:

$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2}+\nabla\left(-\frac{1}{\rho_0}(\nabla p)\right)=\mathbf{Q} \qquad (3)$$

where ρ_0 is the density (kg/m^3), c_s is the speed of sound (m/s), and **Q** is the source (1/s^2). The combination $\rho_0 c_s^2$ is called the adiabatic bulk modulus, commonly denoted by *K*. The density and speed of sound are assumed to be constant because they vary with time on scales much larger than the characteristic acoustic wave period. In our case the source **Q** is null.

The PUNDIT equipment provides a means of generating a pulse, transmitting this to the structure under test, receiving and amplifying the pulse, measuring and displaying the first arrival time. The excitation wave is an acceleration signal, obtained by the piezoelectric transducer, which was applied an impulsive voltage signal shown in Fig. 4 and approximated by the following function

$$Input(t)=-Ae^{-\frac{t}{\tau}}\ ,t>0\ [V] \qquad (4)$$

where **A** (that is 250, 500 or 1200 V) is the maximum amplitude of the signal and τ is the time constant. This voltage is applied to the upper part of the emitter transducer, while the bottom part of both the transducers is grounded.

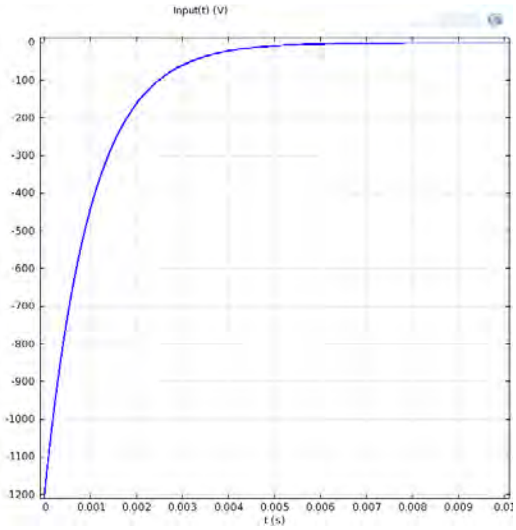

Figure 4. PUNDIT 1200V excitation pulse modeled by COMSOL

For the piezoelectric material (PTZ-4), the default Global coordinate system is used in order to have a material oriented in the *rz*-plane.

The boundary conditions are "axial symmetry" on the z-axis and "sound hard boundary (wall)" on the outside, where the normal component of the pressure vanishes. At the interface between the emitter and the materials, the boundary condition is set to "normal acceleration":

$$\vec{n}\cdot\left(\frac{1}{\rho_0}(\nabla p)\right)=\vec{a}_n \qquad (5)$$

where $\vec{a}_n$ is the normal acceleration.

The other interfaces are continuity boundaries, by default.

5. Results

The models have been solved in the range 0-0.5 ms, with a time step of 1µs. The simulations of the reference bar of aluminum have been done using the voltage with a maximum amplitude equal to 250 V. In Figure

5 the signal received by the second transducer is shown.

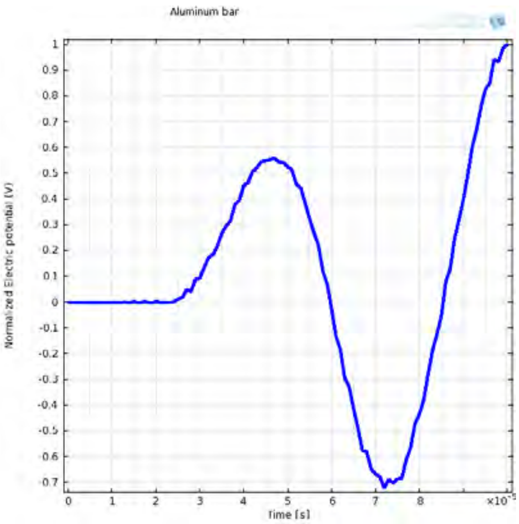

Figure 5. Simulated received signal

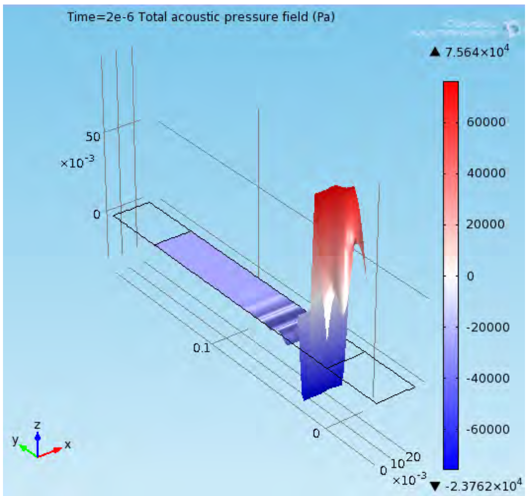

Figure 6. Pressure field at time 2μs

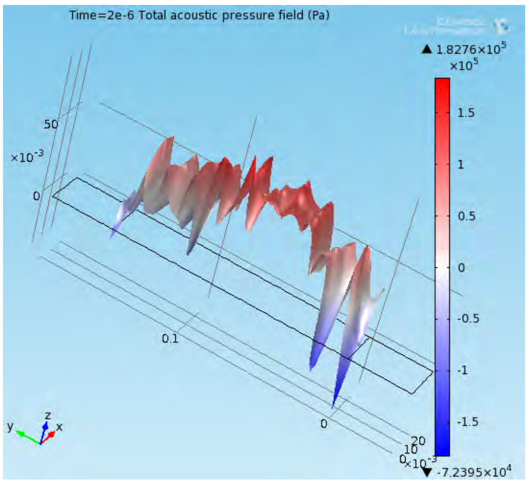

Figure 7. Pressure field at time 24μs

As it can be noticed, the travel time is equal to recorded transmission time.

The simulated pressure fields in the aluminum bar for two different time instants are shown in Figures 6 and 7.

Afterwards the input voltage signal with maximum amplitude of 1200 V has been applied on three points of the trachite wall. Using the experimental equipment, three delayed signals are received on the opposite surface of the wall. The experimental output signals were all attenuated, but for each of the three paths we detect a different harmonic content and a different attenuation. In particular the waveform corresponding to path 3 results strongly attenuated and delayed, due to the presence of the cavity.

The simulated received signals corresponding to three different paths in the wall are reported in Figures 8, 9 and 10.

Unfortunately, the experimental waveform amplitude and form result influenced by the coupling between structure and transducer. Indeed, the transducer is pressed by the operator directly against the wall, and coupling is achieved by the presence of a thin fluid layer inserted between them. Probably the rough surface of the wall do not allow a good contact coupling.

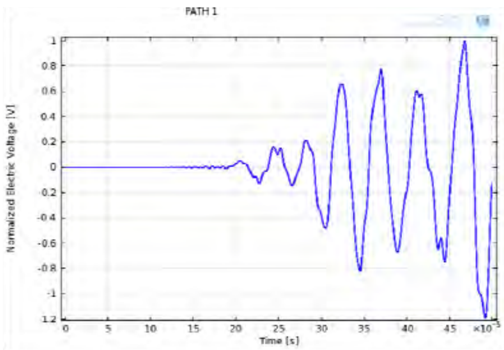

Figure 8. Output simulated signal detected for path 1

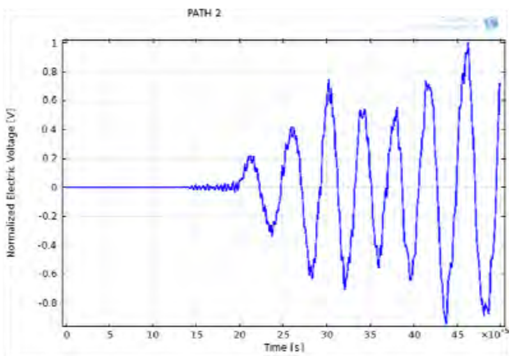

Figure 9. Output simulated signal detected for path 2

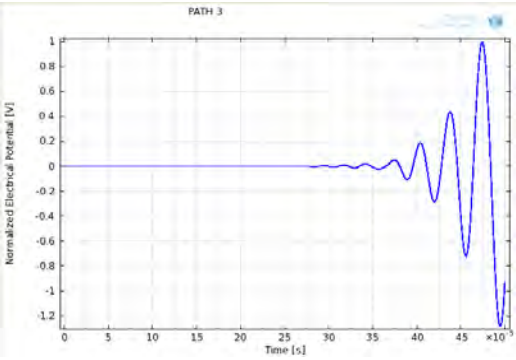

Figure 10. Output simulated signal detected for path 3

Thus, it is crucial to eliminate the variability associated with this contact coupling in order to assure the repeatability of the tests. Moreover, the waveforms appear corrupted by environmental noise.

Nevertheless, there is a substantial agreement among the measured and simulated travel times. In Table 2 the travel times measured with the PUNDIT instrument are reported.

Table 2: Measured travel times

	Measured travel times
Path 1	159 μs
Path 2	179 μs
Path 3	279 μs

Figure 11-13 show the pressure field along the wall computed by COMSOL in the three cases. As it can be noticed, the presence of the cavity causes a strong attenuation of the acoustic pressure field (Fig. 13).

6. Conclusions

In this paper a numerical model for the generation and reception of ultrasonic waves through piezoelectric transducers, using the finite element method, has been performed. To validate the model, ultrasonic tests were carried out with the Direct Transmission Technique using the equipment PUNDIT. The test structure is a trachite wall with an inside cavity. Preliminary results showed an agreement between the waveform arrival times. Nevertheless, further experiments have to be performed in order to reduce the measurement noise and enhance the quality of the coupling.

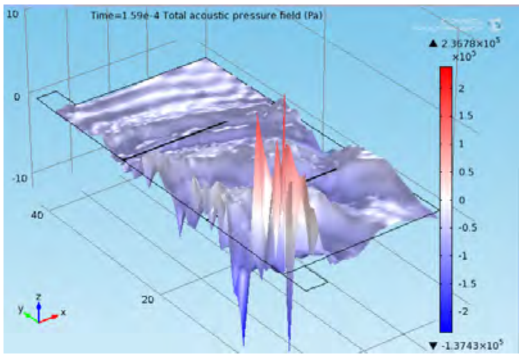

Figure 11. Pressure field at time 159μs for path 1

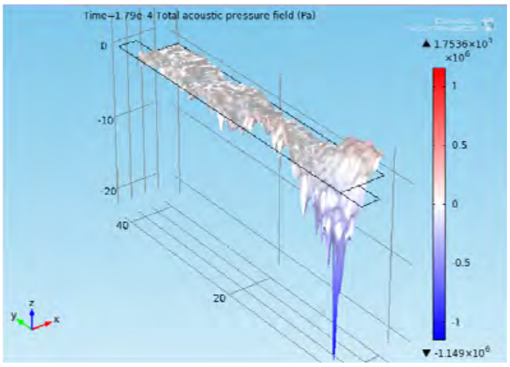

Figure 12. Pressure field at time 179μs for path 2

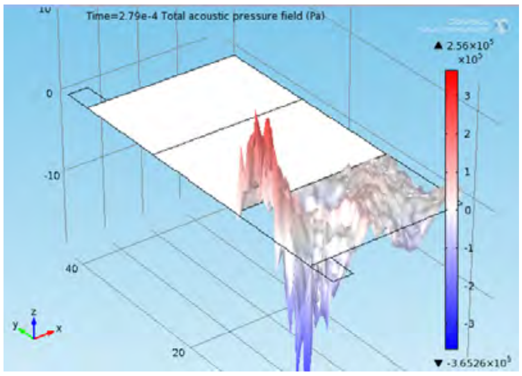

Figure 13. Pressure field at time 279μs for path 3

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8. Acknowledgements

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