



# Improvements of the Ultrasonic Tomography for Applications to Historical Masonry Constructions

Domenico Camassa<sup>1</sup>, Anna Castellano<sup>2</sup>(✉), Aguinardo Fraddosio<sup>1</sup>,  
and Mario Daniele Piccioni<sup>1</sup>

<sup>1</sup> Department of Civil Engineering Sciences and Architecture,  
Polytechnic University of Bari, Bari, Italy  
domenicocamassa@gmail.com, {aguinaldo.fraddosio,  
mariodaniele.piccioni}@poliba.it

<sup>2</sup> Department of Mechanics, Mathematics and Management,  
Polytechnic University of Bari, Bari, Italy  
anna.castellano@poliba.it

**Abstract.** Non-destructive tests play a crucial role for rehabilitation, restoration and strengthening of historical masonry constructions: this justifies increasing research interests on this issue. In particular, sonic and ultrasonic tomography are among the most used NDT techniques for applications to historical constructions since they are relatively fast, reliable and inexpensive. Anyway, the resolution and the capability of those techniques in assessing hidden defects, voids, damage, the masonry layout and the mechanical properties of masonry can be further substantially improved. To this aim, several issues about the experimental setup, the modeling of propagation phenomena of acoustic waves, and the inversion algorithms should be addressed. In this paper some improvements of the ultrasonic tomography for masonry constructions are proposed, based on the implementation of advanced inversion algorithms, on the use of the information about wave attenuation (attenuation tomography) in addition to those related to the time of flight of acoustic waves, and on the enhancement of the experimental setup, in particular for what concerns the coupling between probes and masonry. With reference to tuff samples having known internal defects like holes, cuts and inclusions, the capability of the proposed approach is compared with the standard ultrasonic tomography. The experimental results show the effectiveness of the proposed approach, and suggest some directions for further improvements.

**Keywords:** Ultrasonic tomography · Masonry · NDT techniques  
Inversion algorithms · Amplitude tomography

## 1 Introduction

Historical and archaeological buildings represent the history and the identity for any community, and then it is crucial to preserve this valuable heritage. The availability of preliminary effective diagnostic testing techniques is essential for an accurate and

suitable design of repair, restoration and retrofit interventions [1]. Moreover, for the purpose of the preservation non-destructive techniques are the most appropriate [2, 3]. Among the latter, here the attention is focused on acoustic tomography, and in particular on ultrasonic tomography due to the better resolution and capability with respect to sonic tomography.

Acoustic tomography is an inverse method based on the analysis of the propagation of mechanical waves in a solid domain. In particular, starting from measurements made on the boundary of the domain, certain properties of the inner part of the domain are inferred. Indeed, once considered a cross section of the domain, and through a redundant number of measurements of an “observed parameter” related to acoustic wave propagation, acoustic tomography gives an image of the sectional distribution of a “model parameter” related to the observed parameter. Two fundamental issues arise: (1) the choice of the observed parameter and the model parameter, and the mechanical model relating them; (2) the inversion procedure to be used. The latter involves the definition of: (a) an inversion algorithm, (b) a ray tracing method, and (c) a regularization procedure.

For what concerns the application of acoustic tomography to masonry constructions, basically two different model parameters may be reconstructed [4]: the velocity (velocity tomography) or the attenuation (attenuation tomography) of the propagating acoustic waves. Velocity tomography, also known as travel time tomography (TT), is based on the inversion of travel time (observed parameter). Attenuation tomography can be based on two different observed parameters: (1) amplitude tomography (AT) is based on the amplitude of the first peak; (2) frequency shift method is based on the frequency shift of centroid. Travel time tomography is the most common technique, due to the robustness of travel time as the observed parameter. On the contrary, attenuation tomography is rarely applied to masonry constructions and, when it is, substantially only in the form of amplitude tomography. Indeed, albeit the amplitude is a parameter more sensitive to voids and cracks than the travel time (this renders amplitude tomography very interesting for investigation on masonry constructions), the diffusion of amplitude tomography is obstructed by the fact that amplitude measurements are strongly influenced by several physical and operative issues [4, 5].

Here, in view of exploiting the recalled potentiality of amplitude tomography and starting from some results obtained in the research on AT in the geophysics field (see, e.g. [5–7]), some improvements of the amplitude tomography for applications to masonry constructions are proposed. The proposed procedure is called *Standardized Amplitude Tomography* (SAT). SAT procedure is based on a suitable amplitude propagation model and on the use of an experimental tool aimed at the standardization of amplitude measurements. Moreover, an inversion algorithm is proposed with the aim of overcoming some limits of tomography with highly inconsistent data, as is often the case when dealing with masonry constructions. This inversion algorithm is applicable for reprocessing also velocity tomography data. The results presented in short by the present paper will be discussed more in depth in the papers [8, 9], in preparation.

## 2 Acoustic Tomography: Theoretical Background

### 2.1 Amplitude Tomography

Amplitude tomography aims at obtaining the distribution of the material attenuation coefficient in an investigated section of a solid medium. This approach is based on the measurement of the decrease of amplitude taking place during the propagation of a mechanical wave due to the attenuation. Unfortunately, in addition to the material attenuation, there are many others physical phenomena leading to amplitude decrease [5–10]: geometric attenuation; reflection, refraction and mode conversion at interfaces; wave dispersion; scattering and diffraction; radiation pattern of the source; receiving pattern of the receiver (if a PZT receiver) or the spatial sensitivity of the receiver with respect to the direction of the incoming wavefront (if an accelerometer). Anyway, the strict relationship between the attenuation and the mechanical and physical features of the solid medium justifies the relevance given to AT in geophysics.

In view of the development of amplitude tomography procedures suitable for masonry constructions, some operative issues arise: the amplitude of the emitted wave is usually unknown; multipath phenomena could affect the value of the amplitude of the received wave; the coupling conditions of the transducers may vary in an unpredictable way during the test. The latter problem may be ascribed to the thinning of the coupling media, or to the variation of the pressure exerted by the operator on the transducers (in terms of magnitude and distribution), or to the variation of the features (e.g., the roughness) of the investigated masonry surfaces. Thus, an appropriate amplitude propagation model and a suitable experimental technique should take into account all the phenomena and the operative issues above recalled.

For what concerns the amplitude propagation model, one of the most advanced in the literature is the discrete model proposed in [11] for geophysical applications:

$$A_i = A_0 \left( \frac{L_0}{\sum_j L_{ij}} \right)^\beta \left( \prod_j t_j \right) e^{-\sum_j L_{ij} \alpha_j}, \quad (1)$$

where:  $A_i$  is the acoustic wave amplitude measured at the end of  $i$ th ray (in correspondence of the receiver);  $A_0$  is the acoustic wave amplitude measured at an arbitrary distance  $L_0$ ;  $\beta$  is a parameter depending on the geometry of the propagating wavefront (for example,  $\beta = 0.5$  for cylindrical wavefronts and  $\beta = 1$  for spherical wavefronts); the term  $\sum_j L_{ij}$  represents the length of the  $i$ th ray;  $\alpha_j$  is the material attenuation for the  $j$ th pixel (for tomography, the cross section is discretized in pixels); the term  $\prod_j t_j$  allows to consider reflection and refraction phenomena between pixels ( $t_j$  is the transmission coefficient between the  $j$ th pixel and its neighbor). According to [11], for quasi-homogenous media it is possible to assume  $\prod_j t_j = 1$ .

Notice that in Eq. (1) only some physical causes of attenuation, i.e., geometric and material attenuation, are explicitly represented; the other physical and operative issues depicted above are only indirectly represented by the parameter  $\alpha_j$ ; this may introduce some errors in the results. This suggests that further research efforts for improving the amplitude propagation model are needed.

## 2.2 Inversion Algorithms

Tomography is an inverse problem: starting from experimental measurements and through an inversion procedure the distribution of certain model parameters – wave attenuation or wave velocity – is obtained. Thus, the algorithm used for data inversion plays a crucial role. For tomography, many kinds of inversion algorithms have been proposed [12]: matrix inversion methods, iterative methods, etc. The most common inversion algorithm in tomography is an iterative algorithm called Simultaneous Iterative Reconstruction Technique (SIRT). Although for what concerns the convergence SIRT is more stable than other tomographic iterative algorithms, in presence of inconsistent data SIRT presents still some relevant convergence difficulties. Indeed, data inconsistency prevents iterative methods from converging to a unique solution: once the minimum residual is reached, the estimated parameters fluctuate as iterations progress [12]. Notice that data gathered for acoustic tomography of masonry constructions can be very inconsistent: thus, for overcoming the recalled drawbacks of the SIRT approach, the study of new inversion algorithms suitable for the specific application to masonry constructions is needed.

## 3 Proposed Improvements

### 3.1 Standardized Amplitude Tomography

In this paper, a new amplitude tomography approach for masonry constructions aimed at addressing some relevant issues usually neglected in the classical AT is proposed. The proposed procedure is called *Standardized Amplitude Tomography* (SAT). The innovative aspects of this approach are: (1) the employ of a suitable experimental tool for exerting a known and constant force on the transducers during the test; (2) an amplitude propagation model taking into account some physical and operative issues usually neglected in the classical AT.

#### 3.1.1 The Experimental Tool

In general, wave amplitudes acquired during ultrasonic tests depends on the magnitude of the pressure applied by the transducers on the masonry surface. Thus, in view of acquiring consistent data it is important to maintain constant the force exerted by the operator on the transducers. To this aim, an experimental tool consisting in a transducers case provided with a spring arranged on the top has been designed and built. By handling the transducers through this tool, it is possible to apply a fixed force on the transducers, and thus to exert a constant pressure on the masonry surface. In conclusion, if the test conditions are such that it is possible to assume that the thickness of the coupling media does not vary during the test, and that the surface of the masonry is sufficiently uniform, the employ of the above described experimental tool guarantees to have a constant amplitude of emitted waves during the test.

#### 3.1.2 The Amplitude Propagation Model

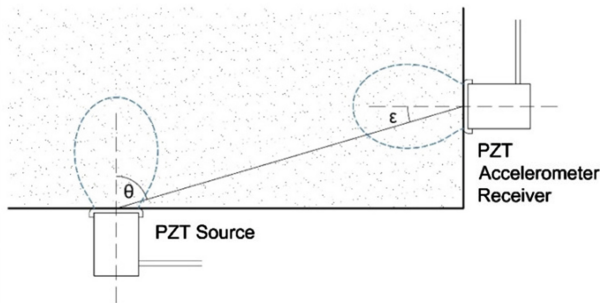
An amplitude propagation model based on the discrete model corresponding to Eq. (1) and aimed at overcoming some limitations of the classical AT approaches is proposed.

Indeed, the proposed model consider: (a) the radiation pattern of the source; (b) the receiving pattern of the receiver (if a PZT receiver), or the spatial sensitivity of the receiver with respect to the incoming wavefront (if an accelerometric receiver). Moreover, the proposed model does not need the preliminary determination of parameters depending on the amplitude of the emitted wave, like  $A_0$  in (1).

In particular, for what concerns the effects of the radiation pattern of the source on the wave amplitude acquired during the test, a directivity function related to the characteristics of the emitter transducer and of the investigated medium is introduced. To this aim, the analytical expression of the directivity function obtained for a cylindrical transducer in the far-field (the Fraunhofer region) is considered. Moreover, for the sake of simplicity the most elementary directivity function is considered, that is, that valid for fluids. Indeed, some numerical experiments show that the latter approximation does not induces substantial errors in the results with respect to the much more complex model needed for isotropic solid media. Thus, the directivity function assumes the form (see, e.g. [10]):

$$D(\theta) = 2J_1(ka \sin \theta)/ka \sin \theta \tag{2}$$

where  $\theta$  is the spatial angle of the source (Fig. 1),  $k$  is the wave number,  $J_1$  is the first order and first kind Bessel function and  $a$  is the radius of the transducers.



**Fig. 1** Radiation pattern of the source with an indication about spatial angle of the source ( $\theta$ ) and spatial angle of the receiver ( $\epsilon$ ).

If an accelerometer acts as the receiver, in order to consider the effects of the spatial sensitivity of the receiver with respect to the direction of the particle motion of the incoming wavefront, a suitable coefficient  $C(\epsilon)$  depending on the specific characteristics of the receiver it is introduced. For example, if the accelerometer is sensitive only in the direction perpendicular to its plate, by geometrical considerations it results  $C(\epsilon) = \cos \epsilon$ , where  $\epsilon$  is the spatial angle of the receiver (Fig. 1). On the other hand, if a PZT receiver with the same pattern of the source transducer it is used, the coefficient  $C(\epsilon)$  must be replaced by the directivity function  $D(\theta)$  of the receiver. Assuming again for  $D(\theta)$  the simply expression valid for a fluid medium, for a cylindrical receiver the

directivity function in the far-field assumes an expression like that in Eq. (2), provided that  $\theta$  must be replaced by  $\varepsilon$ .

Finally, in the proposed model the amplitude of the emitted wave is kept as an unknown parameter. Indeed, the amplitude of the emitted wave depends on the characteristics of the source and on the acoustic impedance between the source plate, the coupling, and the material of the investigated solid, and then this parameter is usually unknown. Thus, the amplitude of the emitted wave has been included within the unknowns constituting the model parameters vector, to be determined in the tomographic inversion of the redundant data acquired during the test; for further detail, see [8].

### 3.2 Inversion Algorithm

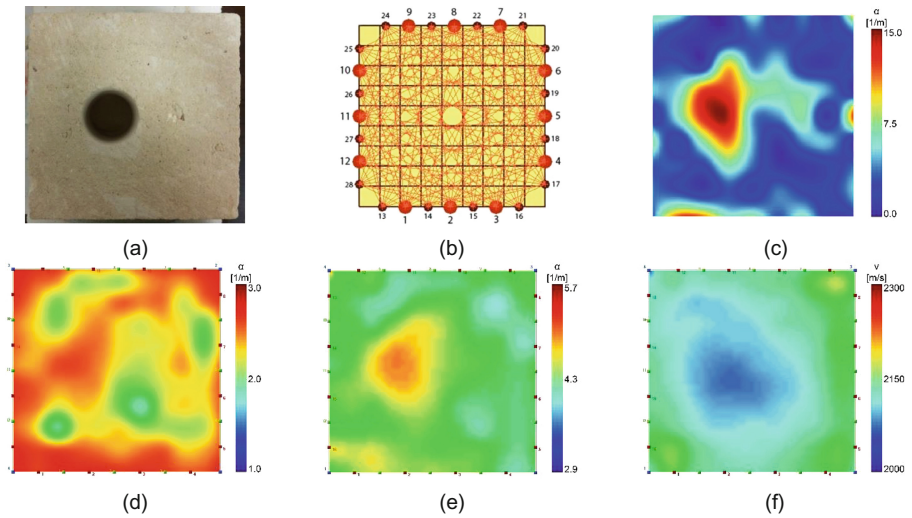
In order to overcome the limit of the SIRT approach in presence of inconsistent data (see Sect. 2.2), an inversion algorithm based on a random walk optimization process has been also studied, which allows to explore the “model space”, i.e. the space of the parameters of the model [13], to minimize a suitably chosen objective function. Notice that the implementation of an optimization technique has the advantage that the objective function chosen to explore the model space can be whatever. For example, is possible to use the ordinary  $l_2$  norm of the residuals or, in view of a more efficient treatments of data inconsistency and outliers (see [14]), the Cauchy norm  $l_C$  of the residuals. Furthermore, the adopted algorithm is robust with respect to local minima traps since it is based on a random walk process. On the other hand, this algorithm is computationally onerous.

Several numerical tests have been performed: it emerges that the proposed inversion algorithm is very efficient for the application to acoustic tomography to masonry constructions, since it allows to explore the model space with various criterion (objective functions), so that data inconsistency can be better handled. These aspects together with the capability of the proposed approach for the tomography of masonry constructions are in depth discussed in [9].

## 4 Experimental Validation

For an experimental validation of the proposed SAT approach, tuff samples having known internal defects like holes, cuts and inclusions have been analyzed. Among the various tests carried out, for the sake of brevity here only the representative case of a tuff block with cross section dimensions 24.5 cm  $\times$  24.0 cm, in which a hole with a diameter of 6.5 cm was drilled (Fig. 2a), it is reported; [8, 9] contain a broader discussion of the obtained results. For the tomography, 144 measures have been taken (Fig. 2b).

The following experimental setup has been employed: an ultrasonic PZT source having a nominal frequency of 55 kHz and an accelerometer as the receiver; plasticine was used as the coupling medium. Both for the source and the receiver, two experimental tools to even out the pressure were used (see Sect. 3.1.1); in particular, those tools were set in order to obtain a force on the transducers of about 50 N. For data



**Fig. 2** (a) Pierced tuff block. (b) Measuring grid; big and small circles represent source and receiver locations, respectively. (c) Attenuation map obtained by SAT through the proposed inversion algorithm. (d) Attenuation map obtained by AT and by SIRT inversion. (e) Attenuation map obtained by SAT and by SIRT inversion. (f) Velocity map obtained by TT and by SIRT inversion (f).

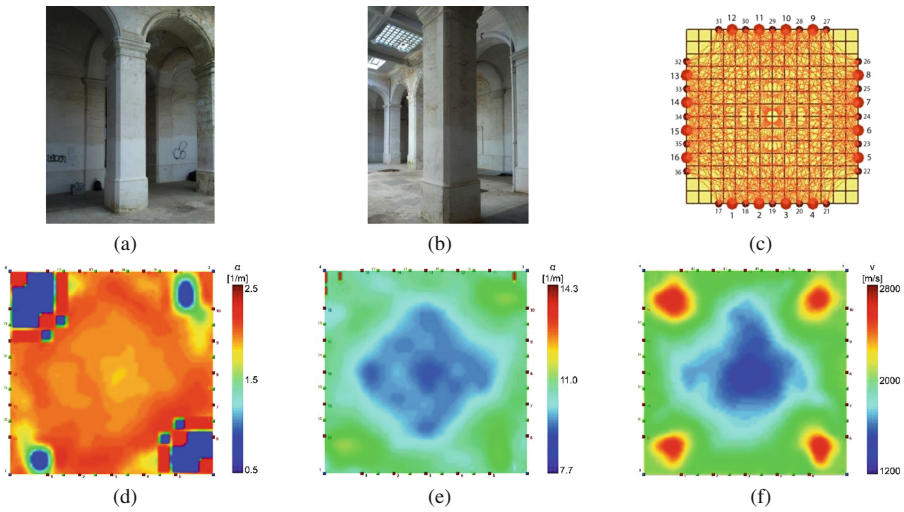
processing, some Matlab [15] scripts were created, and for the tomographic inversion both a commercial software based on SIRT inversion algorithm and the random walk inversion algorithm described in Sect. 3.2 were used.

In Fig. 2c–f the obtained tomographic results for the examined tuff specimen are shown: in particular, Fig. 2c is the attenuation map obtained by SAT and by the proposed inversion algorithm; Fig. 2d is the attenuation map obtained by the classical AT and by the SIRT inversion algorithm; Fig. 2e is the attenuation map obtained by SAT and by the SIRT inversion algorithm; Fig. 2f is the velocity map obtained by TT and by the SIRT inversion algorithm. Notice that the latter corresponds to the most common and conventional tomographic approach for masonry. In Fig. 2c–f, blue colors indicate areas with low attenuation (for the attenuation maps) or with low velocity (for the velocity map), respectively.

A first comparison can be made between the different approaches for the same inversion algorithm (SIRT inversion, Fig. 2d–f). It is clear that the results of AT (Fig. 2d) are meaningless, since they do not allow for identifying the defect. Conversely, SAT results (Fig. 2e) allow for locating the hole quite accurately and are quite better of the results obtained by TT (Fig. 2f). Moreover, if SAT it is coupled with the new random walk inversion algorithm, using the standard  $l_2$  norm and without regularization (Fig. 2c), the results are comparable with those obtained by the standard SIRT inversion: this confirms the reliability of the proposed inversion algorithm.

## 5 Application of the Amplitude Tomography to a Masonry Pillar

SAT has been applied to a masonry pillar with cross section dimensions  $96.5\text{ cm} \times 96.5\text{ cm}$  and covered by plaster (Fig. 3a–b), belonging to an ancient tobacco factory in Ostuni (Apulia, Italy). The plaster guarantees the uniformity of the surface of the pillar, in terms of impedance and roughness of the surface. For the tomography, 240 measures were taken (Fig. 3c), and for the inversion the conventional SIRT algorithm has been used.



**Fig. 3** (a–b) The masonry pillar. (c) The measuring grid; big and small circles represent source and receiver locations, respectively. (d) Attenuation map obtained by AT. (e) Attenuation map obtained by SAT. (f) Velocity map obtained by TT.

Also in this case the AT map (Fig. 3d) is meaningless, whereas both SAT attenuation map (Fig. 3e) and conventional TT velocity map (Fig. 3f) allow for identifying a square inner core of the pillar, characterized by low values of the material attenuation and of the velocity respect to the external layer. These different acoustic features are coherent with the building techniques used for similar contemporary buildings in Ostuni area.

## 6 Conclusions

Experimental results obtained for laboratory specimens and for a true structural element show that the proposed *Standardized Amplitude Tomography* (SAT) can substantially improve the capability of the amplitude tomography (AT) for applications to masonry constructions. This innovative approach is based on a suitable amplitude propagation



model and on the use of an experimental tool for the standardization of the measurements. The accuracy of the tomographic results may be further improved by adopting the proposed random walk inversion algorithm, which better manages the inconsistent data gathered on masonry constructions.

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