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Prospective of the application of ultrasounds in archaeology

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Abstract. This paper presents a prospective analysis of non destructive testing (NDT) based on ultrasounds in the field of archaeology applications. Classical applications of ultrasounds techniques are reviewed, including ocean exploration to detect wrecks, imaging of archaeological sites, and cleaning archaeological objects. The potential of prospective applications is discussed from the perspective of signal processing, with emphasis on the area of linear time variant models. Thus, the use of ultrasound NDT is proposed for new ceramic cataloguing and restoration methods.

1. Introduction

The principal objective of this paper is to provide a prospective analysis of the use of non-destructive testing (NDT) by ultrasounds in archaeological applications. NDT by ultrasounds is a powerful technique of material diagnosis and characterization that has been applied in a wide variety of applications including distance gauging, corrosion monitoring, and flaw detection [1]. Briefly, this technique operates in two modes: pulse-echo (an ultrasound sensor or transducer is used both as emitter and receiver) and trough-transmission (two transducers, the first one is used as emitter and the second one is used as receiver). Figure 1 shows a chart summarizing the principal techniques of characterization and dating used currently in archaeology. Contrary to NDT methods, most of these techniques require some destruction of the analyzed materials, expensive equipment, and tube preparation, and thus, they are costly and time-consuming.There are relatively few references of the applications of ultrasounds in archaeology, and in general, they can be roughly organized into four classes: imaging, cleaning, flaw detection, and material characterization.

Imaging applications consists of obtaining tomographic representations of underground and underwater archaeological sites and objects. Some examples of this application are the following: imaging of the stern section of a shipwreck obtained by an ultrasound triangulation system composed of three receivers and two emitters [2]; an experimental setup for underwater artefact identification [3]; a cave internal structure based on a 3D model from ultrasound reflections, which was used for several simulations including the sediment flow inside the cave [4]; underground interface estimation to be used in exploration of comparatively large archaeological sites [5]; and a precise localizer and sketcher of archaeological findings after they are extracted by archaeologists [6]. The use of ultrasounds for cleaning in archaeology have covered applications such as ultrasound brushing of archaeological metal-made objects [7], isolating a suspension of binder carbonates from bulk mortars in mortar radiocarbon dating [8], and removal of contaminants in archaeological bone analysis [9].

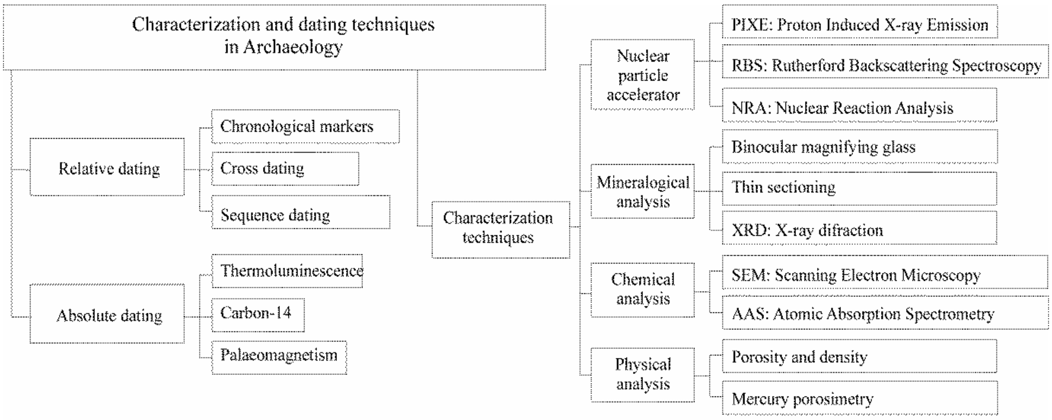

Figure 1. Classical archaeological characterization and dating techniques.

Some examples of flaw detection applications are the following: visualization of the internal structure of historic relics in wooden pillars of shrines from estimation of the time-of-flight in several measurements through the pillar surface using fan-beam geometry [10]; diagnosis of ancient wooden panel paintings (detection of delaminations between superimposed priming layers and wood support and cracks in the priming layers itself) by using air-coupled ultrasonic technique [11]; 3D microtomography for visualization and reconstruction of voids and cracks within, internal structures, restorative interventions, and the cuts through the original cast works in sculptures [12]; and integrating ground-penetrating radar (GPR) and ultrasounds to evaluate the condition of a Roman marble slab after a fall down during transportation [13]. Finally, ultrasounds also has been employed for archaeological material characterization, for instance, examining weathering processes and intensity acting of humidity and salt in the rocks of historical buildings at Alhambra, Spain [14] and determination of mechanical properties (Young's modulus and Poisson's ratio) for prehistory lithics from Armorican massif in western France [15].

Recently, we proposed an application of ultrasounds for cataloguing archaeological ceramics according to the chronological period of the analyzed pieces (for instance, Bronze age, Roman, Middle ages, etc.) [16]. The cataloguing method employed a versatile classifier based on mixtures of independent component analyzers [17] which has been successfully applied to NDT problems [18]. In the next section, we discuss prospectively the extension of this method to new applications based on modeling the ultrasound signal by means of a linear time variant model.

2. Ultrasound signal modelling as a linear time variant system

In general, exact knowledge of the behavior of and ultrasonic pulse travelling inside a material is a complex matter. This is especially true in ceramic materials, where the ultrasonic waves suffer strong effects of attenuation, dispersion and backscattering. Nonlinear wave acoustic propagation theory is hence claimed for a detailed prediction of the sensor recorded wave for a given ultrasonic excitation of the material [19]. Things become even more complicated in restored ceramic due to the interactions between the original material and the one used for restoration. However, from the perspective of classification or cataloguing of ceramics pieces into a finite (not too large) number of classes, simpler linear or nonlinear models may be enough to justify the use of some signal extracted features (see table 1).

Thus, a simple model may assume that the material is formed by many small reflectors (reflectivity of the material). When the ultrasonic pulse impinges in a reflector, a new pulse is generated. The recorded signal would be the superposition of the many pulses thus generated by the material microstructure. This essentially relates to consider a linear system model where the input is the reflectivity of the material and the impulse response is the ultrasonic pulse excitation. Hence the output of the linear system (recorded sensor signal) would be the convolution of the reflectivity and the excitation pulse. Figure 2 shows a scheme of the ultrasound through-transmission LTV model.

Table 1. Examples of features extracted from ultrasound signal.

Total signal attenuation	$\hat{x}(t) = Ae^{-\beta t} \Rightarrow Aten\_Total = \beta$	Attenuation curve initial value (dB)	$\hat{x}(t) = Ae^{-\beta t} \quad Po = 10\log(A)$
Propagation velocity	$v = \dfrac{piece\ thickness}{ultrasound\ time\ of\ flight}$	Centroid frequency	$fc = \dfrac{\int_{f_1}^{f_2} f \cdot \lvert X(f)\rvert df}{\int_{f_1}^{f_2} \lvert X(f)\rvert df}$
Principal frequency	$f_{max} / \lvert X(f_{max})\rvert \geq \lvert X(f)\rvert \forall f$	Time-reversibility	$\dfrac{1}{\sigma_x^3}\left\langle \left(\dfrac{dx(t)}{dt}\right)^3 \right\rangle$
Principal frequency Amplitude	$\lvert X(f_{max})\rvert$	Third order autocovariance	$\langle x(t) \cdot x(t-1) \cdot x(t-2) \rangle$
Signal power	$P\_Total = \dfrac{\int_0^T \lvert x(t)\rvert^2 dt}{T}$	Instantaneous centroid frequency	$fc(t = t_0)$

In the simplest case, the pulse (impulse response) may be considered to be constant, which means that the pulse arriving at every reflector of the microstructure is always the same and that the only effect of the reflector is to generate a new replica with given amplitude, depending on the reflector size. This corresponds to a strictly linear time invariant (LTI) system in the context of system theory. More complex models may be gradually considered depending on the complexity of the material. Thus, a frequency independent attenuation of the pulse can be easily introduced into the model by assuming a linear time variant (LTV) system. This can be generalized to frequency dependent attenuation by allowing a general distortion of the pulse as it propagates deeply into the material. Also, some nonlinear effects may be considered by, for instance, allowing some zero-memory nonlinear transformation before or after the LTV system.

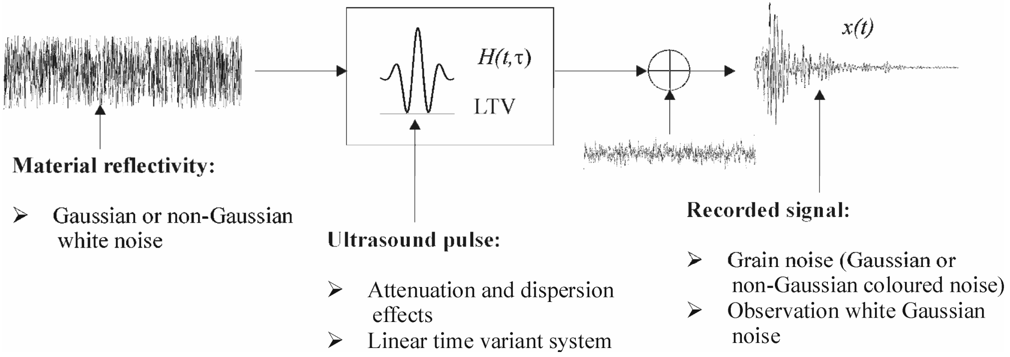

Figure 2. Ultrasound through-transmission LTV model.

In any case, what it is important from the perspective of the work described in this paper is that these models (apart from simulation use) may inspire about possible features for classifying the material. It is clear that those features should be related to the input (reflectivity) or to the system itself (impulse response or zero-memory nonlinear function, for example). Reflectivity may be considered a stochastic process and so statistical features directly obtained from first, second or higher order statistics are reasonable candidates. These features may be stationary or non-stationary, depending on the nature of the material. For example in the restoration framework, the obtained features should change in areas where the restoration material is present in comparison with areas where it is not: the form that a given statistics varies with depth suggests a signature for classification purposes between different qualities of restoration.

Regarding the impulse response or other models of the systems, we can try to estimate them in time or frequency domain from the recorded signals. Thus, we can make spectral analysis to smooth spectral estimates of the system frequency response. This can be made assuming an LTI model or a LTV model (time-frequency spectral analysis). Then some signatures and parameters can be computed from the estimated spectra to be used as features at the classifier input.

3. Conclusion

The standardization of an efficient and non-destructive method for ceramic characterization based on ultrasonic testing will be an important contribution for archaeologists. This method could complement or replace destructive, costly, and time-consuming techniques, which are currently being used by archaeologists in the area of ceramic characterization. We have discussed here the possibility of devising NDT by ultrasounds for archaeological ceramic classification from the perspective of linear time variant modelling. The differences in physical properties, composition and processing of the materials allow the extraction of signatures by using ultrasound signals.

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