ULTRASONIC SIGNAL PROCESSING FOR ARCHAEOLOGICAL CERAMIC RESTORATION

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ABSTRACT

This paper presents an application of ultrasonic signal processing to find parameters related with physical properties of archaeological ceramic pieces and consolidation products used in their restoration. Pieces consisted of ceramic fragments from Bronze, Iberian, Roman and Middle ages. Ultrasonic signals measured from the pieces were processed to derive an ultrasonic signature of the material properties. Signal parameters, such as, wave propagation velocity, dominant frequency, and signal attenuation, were estimated. Parameters were processed by linear discriminant analysis obtaining a good fitting for archaeological period classification. Ultrasonic signature based on centroid frequency evolution was dissimilar for different consolidation products. Ultrasound propagation velocity and others parameters were related with the material porosity.

1. INTRODUCTION

Non-destructive evaluation (NDE) by ultrasound is a very useful technique used in fields such as construction, food, and biomedicine. The technique has basically two operation modes: pulse-echo (one sensor as emitter and receiver) and transmission (one emitter and one receiver). An ultrasound pulse is injected in the inspected material and a response of the material microstructure is received [1,2]. The measured signal can contain echoes produced from discontinuities, inhomogeneities, borders of the material, plus material grain noise (superimposition of many small echoes due to the material microstructure). All of this information can be used for quality control and characterization of materials [3,4].

Ultrasound has been used in archaeological applications such as, ocean exploration to detect wrecks, imaging of archaeological sites, cleaning archaeological objects [5-7]. There are not references of the application of ultrasonic signal processing to support the restoration of archaeological ceramics.

The first goal of this study was to classify according to the porosity different fragments of archaeological pieces after the treatment with consolidation products applied in different concentrations and using different treatments for the consolidation product penetration. Features from the signal were extracted by time-frequency techniques and the classification algorithm was based on linear discriminant analysis (LDA) [8-10].

The second goal was to estimate a parameter from the ultrasonic signal to characterize the used consolidation product and the ceramic itself. The technique used for material characterization was the ultrasonic signature based on the evolution of the ultrasound pulse centroid frequency through different depths of the material [11,12].

The set of analyzed pieces consisted of 16 fragments for each one of the periods: Bronze, Iberian, Roman, and Middle age and selected from ceramics belonging to the Requena's archaeological museum at the East Spain. Pieces were made of cooked mud with different manufacturing techniques being the most common in the *Valencian* region.

For the restoration of the pieces, the following consolidation products were used: Paraloid (ethyl metacrylato) B-72, Acryl (acryl resin) 33 and Estel (ethyl sylicate) 1000. Each one of the pieces was treated with one of the consolidation products at 5% or 10% concentration using one of two methods for product penetration: impregnation and immersion [13].

The following sections describe the ultrasound NDE method used for testing the pieces, the parameters extracted from the recorded ultrasonic signal, the classification procedure and results, an ultrasonic signature analysis and findings of material characterization, and finally the conclusions and future work.

2. FEATURE EXTRACTION FROM ULTRASONIC SIGNALS

The equipment setup used for NDE of the archaeological ceramic pieces was the following:

Ultrasound equipment setup		**Acquisition equipment setup**	
Ultrasound equipment	*Matec PR5000*	Acquisition equipment	*Handyscope HS-3*
Transducers	*2.25 MHz Krautkramer*	Sampling frequency	*100 MHz*
Pulse width	*4 μs*	Sample number	*10000*
Pulse amplitude	*100%*	Observation time	*1 ms*
Analog filter	*None*	Vertical resolution	*16 bits*
Excitation signal	*Tone burst 1.050 MHz*	Dynamic range	*100 mV/division*
Operation mode	*Through-transmission*	Average	*16 acquisitions*
Amplifier gain	*43 dB*	PC connection	*USB*

Table 1. Equipment setup

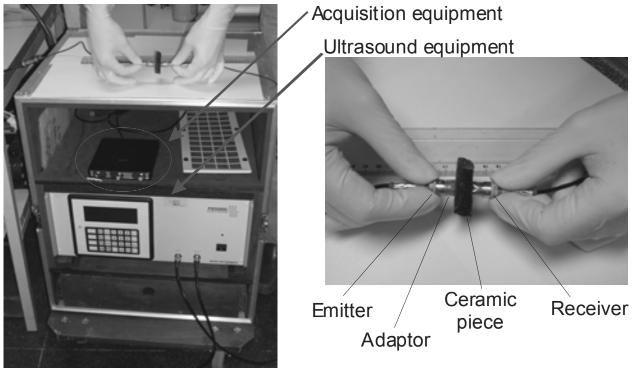


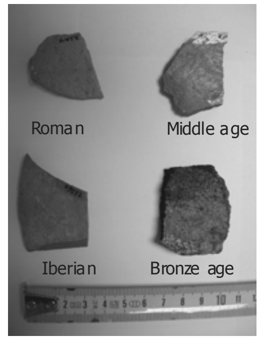
Fig 1. Equipment and detail of ultrasonic testing

Pieces were measured one time by transmission mode, using a rubber adaptor, see Figure 1. This coupling method was selected due to good ultrasonic transmission and to be innocuous for the pieces, after trying with methods such as immersion and direct contact. This latter (contact by gel) offers a very good coupling but the time for measuring is very short to avoid gel absorption by the piece.

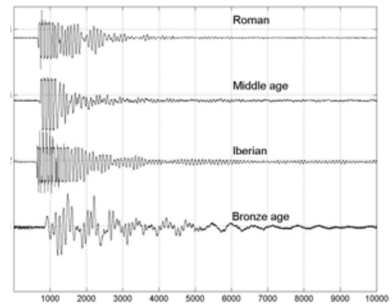
Figure 2a shows some of the pieces and Figure 2b shows the ultrasonic signals extracted from those pieces. In order to test the sensitivity of the ultrasonic signals to changes of material physical properties from different ages, various parameters for classifying were calculated from the signals. The ultrasonic parameters -features- and the formulas used for their calculation are in Table 2, where $x(t)$ is the recorded signal and $X(f,t)$ is the Short Time Fourier Transform. The first 6 parameters were used for classification and the last one –centroid frequency– was used to analyze the signature of the material properties.

Ultrasonic parameter	Formula
Propagation velocity	$v = \dfrac{\text{piece thickness}}{\text{ultrasound time of flight}}$
Principal frequency	$f_{max} = \underbrace{max}_{f} \lvert X(f,t) \rvert$
Principal frequency attenuation (dB)	$x_i(f,t) = TF^{-1}\{X(f,t) \cdot Notch_{filter,f_i}(f)\}$ $x_i(f,t) = Ae^{-t\beta_i} \Rightarrow At\_F\,\mathrm{Re}son = \beta_i$
Signal power	$P\_Total = \dfrac{\int_0^T \lvert x(t) \rvert^2 dt}{T}$
Total signal attenuation	$x(t) = Ae^{-\beta t}$ $Aten\_Total = \beta$
Attenuation curve initial value (dB)	$x(t) = Ae^{-\beta t}$ $Po = 10\log(A)$
Centroid frequency	$fc(t) = \dfrac{\int_{f_1}^{f_2} f \cdot \lvert X(f,t) df \rvert}{\int_{f_1}^{f_2} \lvert X(f,t) df \rvert}$

Table 2. Features space for classification and material signature



2a. Some analyzed pieces



2b. Ultrasonic signals

Fig 2. Ultrasonic signals measured from archaeological ceramics

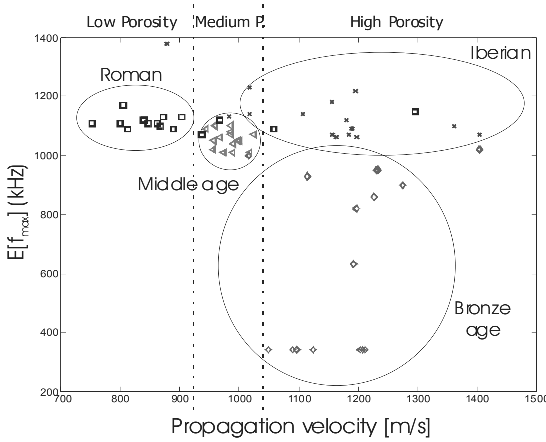


Fig 3. Propagation velocity vs. Principal frequency

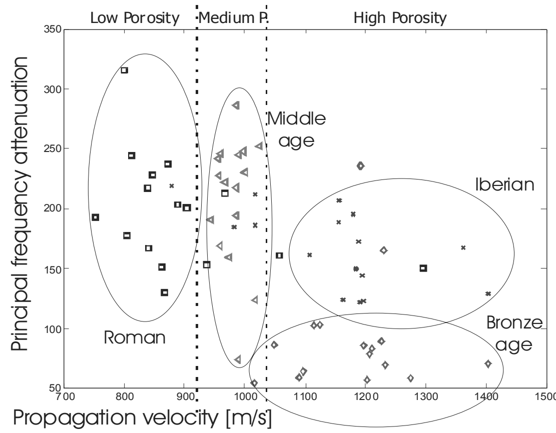


Fig 4. Propagation velocity vs. Principal frequency attenuation

3. STATISTICAL CLASSIFICATION

Figures 3 and 4 are scatterplot diagrams of the ceramic pieces set using two features: propagation velocity vs. principal frequency and propagation velocity vs. principal frequency attenuation. In these bidimensional feature subspaces the ceramic pieces were classified according to age with a high percentage of success with few misclassified pieces.

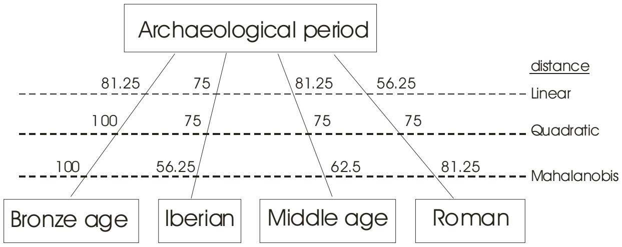


Fig 5. Classification results of archaeological ceramics

In addition, Figures 3 and 4 show two values of propagation velocity around 920 and 1040 m/s, which can be used as thresholds to determine porosity differences for the ceramics from different periods. The resulting clusters were highly correlated with *a priori* knowledge on the kind of ceramic porosity.

Precision of the previous bidimensional classification was improved adding more features to the classification space that allows increasing the separation of the disjoint subspaces or classes that the pieces belong to. For this study the complete classification space was composed by 6 features and the cases were 64. The total of 384 data were processed by a classifier based on LDA with four defined classes corresponding to each one of the ceramic archaeological periods, i.e., Bronze, Iberian, Roman and Middle age.

Classification procedure followed a supervised scheme with 5 steps: i.) Label the database cases with the known archaeological period, ii.) Select a case of the database, iii.) Estimate an archaeological period for the selected case by LDA algorithm using the remaining cases as training data, iv.) Repeat steps ii and iii until the end of the cases, and v.) Calculate the percentage of success for classification results.

Basically the classifier works calculating distances between the cases (pieces) and separating them in disjoint classification subspaces. Then various distances were tried (linear, quadratic, and mahalanobis), obtaining high average values of success in the classification (linear: 73.44%, quadratic: 81.25%, mahalanobis: 75%) to determine the historic period of the piece, see Figure 5.

Classification of the archaeological ceramics from ultrasonic signal parameters worked well, independently of the treatment applied to the pieces with different consolidation products. Besides of classifying the pieces according to the archaeological period, others classifications were tried, such as, classifying by archaeological period and consolidation product and classifying by archaeological period and consolidation method.

Both results for those classifications were low success percentages due to the few number of cases for the number of classes, 12 and 8 respectively. Classifying only by consolidation product or method has no sense in the present application because the features of the ultrasonic signals separate the pieces firstly according to their archaeological period instead of the consolidation product or method.

4. ULTRASONIC SIGNATURE ANALYSIS

Additionally to the classification procedure, an analysis of the physical characteristics of the pieces treated by consolidation products was made by calculating an ultrasonic signature. The ultrasonic signature consists in the evolution curve of the central frequency of the injected ultrasonic pulse while it propagates inside the material.

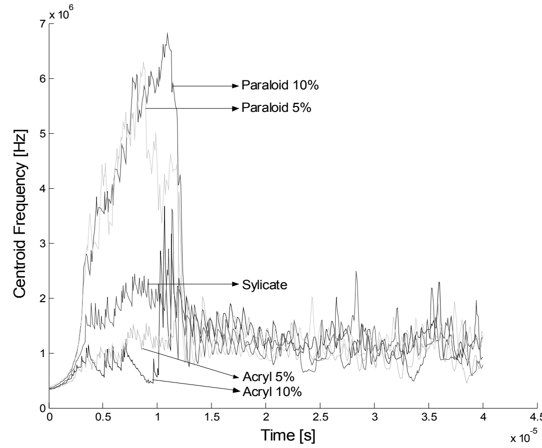


Fig 6. Ultrasonic signature by centroid frequency evolution in Middle Age pieces for the different consolidation products

The centroid frequency evolution is related to the way the different frequency components of the pulse spectrum progressively are attenuated. In general, the frequencies attenuate in a different way causing spectrum variations and consequently the central frequency of the pulse varies. These variations are inherent to the physical properties of the material and can enable its characterization. The technique to obtain the ultrasonic signature is made by a non-stationary analysis of the grain noise at different penetration depths of the pulse and it has two steps: estimation of the pulse spectrum and estimation of the central frequency of the spectrum.

Grain noise is generated by the superposition of multiple echoes caused by the material microstructure, when an ultrasonic pulse with a suitable frequency is injected in the material. Grain noise can be modelled stochastically and spectral techniques can be applied to the model to extract parameters and correlate them with material physical properties, allowing its characterization. A classic method to analyze the dependence of the attenuation with the frequency is measuring the significant frequency through the grain noise spectrum. The instantaneous centroid frequency, the one corresponding to the maximum energy, and the resonance frequency feature certain variation with depth due to the dependence with the frequency attenuation [14].

Figure 6 shows the evolution of the centroid frequency in the signal record time for the middle age ceramics consolidated by the impregnation method. This 5-piece set features a dissimilar ultrasonic signature for each case, i.e., the signature of the consolidation product (acryl, paraloid, sylicate) used in the ceramic can be discriminated. This result of high correlation between the ultrasonic signature and the material properties was obtained in some subsets of the analyzed pieces.

All the values of centroid frequency evaluated at the material depth corresponding to 15 μs of the signal record, for the ceramics consolidated by the impregnation method, are shown in Figure 7. A correlation between the centroid frequency values and the archaeological periods exists. This correlation is related with the material porosity property as we found in classification results.

Figure 7 exhibits a variance of the centroid frequency for each period due to the different consolidation products and their concentration applied in the restoration process.

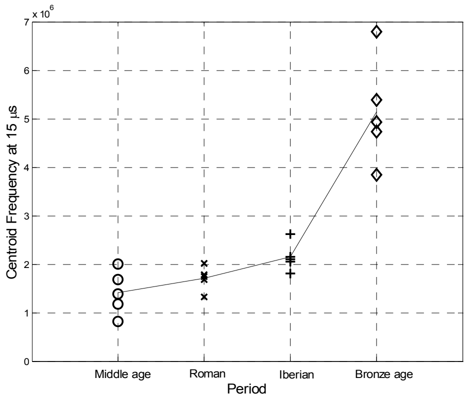


Fig 7. Centroid frequency evolution at 15 µs of the signal record for pieces treated with impregnation method

Variance in Figure 7 allows distinguishing the consolidation products for Middle and Bronze ages as we showed in Figure 6, but for the Roman and Iberian periods there are certain overlapping between their centroid frequency values. This latter make difficult to separate the consolidation products using only the centroid frequency as ultrasonic signature.

Both for the impregnation and the immersion methods of consolidation, the curve traced through the mean values of the centroid frequency of the pieces for the different periods grows monotonically with the ceramic age.

5. CONCLUSIONS AND FUTURE WORK

Utilization of ultrasonic signal processing in archaeological ceramic pieces has been validated by statistical classification and ultrasonic signature techniques. Parameters extracted from the recorded ultrasonic signals were related with the porosity physical property of the analyzed pieces. These parameters are the ultrasound propagation velocity and the centroid frequency.

Classification of archaeological ceramics from ultrasonic parameters worked well, independently of the consolidation treatment applied on the pieces. Six features were used, but they can be extended or modified in order to improve the classification results.

The evolution of the centroid frequency as a material signature featured different behaviour for different kind of consolidation products used in archaeological ceramic restoration. This result was found in some subsets of the analyzed pieces, such as the middle and Bronze Age pieces treated by impregnation. It has to be pursued to find others parameters to characterize the consolidation product for restoration of the analyzed pieces.

Findings of this work open an important research line in the archaeological ceramic restoration. Results have to be refined with more extended studies with the purpose of obtaining a tool based on ultrasonic signal processing for optimization of the consolidation products and methods in the restoration process.

ACKNOWLEDGEMENTS

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