2023 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Rome, Italy, October 19-21, 2023

Acoustic characteristics and defects of adhesion of ancient construction materials using the PICUS system

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Abstract **– The text discusses the applications of the PICUS system in comparison to traditional auscultation techniques for analyzing detachments in historical and artistic artifacts. Non-Destructive Evaluation (NDE) techniques, although valuable for assessing the condition of materials and structures, face limitations in terms of feasibility, optimal operational conditions, and potential risks to delicate objects. In practical work environments, conservator-restorers often rely on traditional auscultation techniques, involving tapping the surface and observing vibrations, due to their accessibility, simplicity, and cost-effectiveness. These techniques provide immediate tactile feedback and insights into the condition and integrity of the artwork. However, they are subjective and rely on the expertise of the conservator-restorer. Overall, a combination of PICUS techniques and traditional auscultation can enhance the understanding of artifacts while considering practical constraints.**

I. INTRODUCTION

When conducting a diagnostic campaign focused on ancient structures of historical, artistic, or archaeological significance, it is essential to recognize these heritage assets as intricate, multi-layered systems. Artifacts constructed according to strict technical rules using original materials tend to exhibit better preservation. On the other hand, conservation issues are often observed in artifacts produced in less-regulated environments, where both the quality of materials and the transmission of knowledge for proper execution are lacking.

The deterioration of such properties can manifest in various ways, impacting not only the surface but also the entire section of an ancient artifact. Identifying and understanding these defects and their acoustic characteristics is crucial. Additionally, it is important to assess the presence, location, and extent of separations or discontinuities between the layers of the structure.

These separations can arise due to different factors such as earthquakes, conflicts, environmental conditions, aging, material incompatibilities, or previous interventions. Properly documenting and comprehending these separations is vital for a comprehensive assessment of the structural condition of the artifact.

Deterioration phenomena should be adequately represented through graphical documentation and compared with other relevant information such as crack patterns, capillary rise fronts, voids, and gaps. This facilitates an understanding of the causes of deterioration, allows for possible countermeasures, and helps strike a balance between preserving the existing state with minimal intervention. The examination process involves careful analysis and documentation of detected discontinuities by conservation specialists. Traditional specialized auscultation techniques, such as tapping or knocking the surface with one hand while sensing the vibrations with the other, are typically employed. Graphic documentation, including detailed drawings, photographs, and digital imaging, is used by the conservators and restorers to precisely record the location and characteristics of identified separations.

From 2018 onwards, research has been underway to develop an acoustic-electronic method for qualitatively analyzing the presence of detachment and debonding in ancient artifacts. This method, along with a specially designed probe, is referred to as the "PICUS" system, named after the Latin word for "woodpecker."

The PICUS system is a validated automatic system for detecting and measuring detachments and non-visible defects in general [1]. The experimental apparatus comprises a probe with an electromechanical percussion element that taps the surface and generates sound, a force sensor for measuring the impact force, and a microphone. All these components are connected to a low-cost Arduino-type microcontroller. The XY position of the probe is detected by an infrared (IR) camera system.

The proposed technique on the PICUS probe involves comparing an acoustic "snapshot" of the target with a "reference snapshot" using image correlation. By calculating cross-correlation a similarity index is assigned to the Z coordinate, leading to the generation of an accurate map representing the condition of the object.

Currently, the most effective representation of a defect, based on the XYZ values obtained through the PICUS procedure, is a local topographic map. These maps depict the physical features of the artifact surface revealed by the acoustic signals produced by the percussion. To create these maps, a gridding process is employed, utilizing interpolation techniques to estimate Z values at locations between irregularly measured points. The representation may also involve adjusting the offset to reduce unwanted information. Results from the mapping procedure will be compared with those obtained using traditional auscultation techniques.

Fig. 1: In this palimpsest, a Roman wall painting decoration consists of multiple layers, including two phases of painted plaster. The visible losses in the artwork are a direct result of detachments that have occurred between these layers.

Furthermore, the PICUS system allows for two additional types of analysis: one based on the spectral energy distribution of the reflected signal (Wr) [2], and the other based on the calculation of the Impact Time (IT) [3]. Both methods assign the output result to the Z coordinate. Research has been conducted to determine the most reliable method, and the cross-correlation method has been identified as the most suitable for representing defects in architectural structures. The alternative method can be successfully applied to other materials and structures, always assessing conservative conditions through the acoustic response, as demonstrated in this article.

II. DETACHMENT OF MORTAR LAYER IN ANCIENT STRUCTURES PAPER

Ancient structures are a testament to the creativity and skill of artisans from the past, showcasing various forms of artistic expression such as mosaics, wall paintings, stucco reliefs, graffiti, slab coverings, and decorated pavements. While these heritage artifacts are primarily appreciated for their aesthetic value, they possess a complex multilayered structure beneath their surface.
Mortar-based heritage techniques are characterized by a stratified structure. While the simplest configuration may consist of only a support and a coating layer, traditional techniques involve two or more layers of mortar overlapping each other. The thickness of these layers had to be carefully considered to ensure the desired mechanical qualities of the plaster upon drying, taking into account environmental factors. In the context of conservation and restoration, the term "detachment" refers to the discontinuity between superficial layers of material, both among themselves and with respect to the substrate (Fig. 1). This phenomenon often precedes the actual loss of material. In the case of plasters and mortars, which are artificial stone materials, the term detachment is commonly used [4].

The separation between layers has always been an undesirable occurrence, as it can lead to a gradual decay process. Several factors contribute to the detachment of rendering layers that were originally adherent and adjacent to each other. Intrinsic causes, such as execution defects, can be attributed to the formation of adhesion defects between layers. These phenomena often manifest as delamination between different rendering layers or separation from the underlying support. They may also follow the texture of the support, such as a lack of adhesion at mural joints. On the other hand, detachment between layers can also be attributed to external factors like environmental, climatic, and anthropogenic influences that the artifacts have been exposed to over the centuries.

III. THE ACOUSTIC RESPONSE OF A PLASTER DETACHMENTS AS EXPERIMENTALLY OBSERVED

The acoustic characteristics of detachments have been observed experimentally, particularly when a surface is subjected to an impulsive force such as tapping. This generates a sound phenomenon similar to that produced by percussion musical instruments. An analogy can be made with a small kettledrum, where a membrane is firmly fixed at its edges. In the case of detachments, the membrane is replaced by a plate. When the plate experiences impulsive mechanical stress induced by the PICUS probe, it produces sound waves that are influenced by its modes of vibration and the compressibility of the air in the enclosed space beneath it. A solid, high-pitched sound indicates a good condition, while a "dull" sound suggests deterioration.

The Power Spectrum of a time series x(t), such as the audio signals sampled by the PICUS System control unit on a mockup reproducing plaster adhesion defects, describes the power distribution of the sound signal as a function of its frequencies (Fig. 2).

In the case of a hollow or cavity-type detachment, the motion of the plate becomes trapped within the enclosed space, resulting in a longer decay time of the sound compared to an intact area. The time evolution of the signals differs, with the decay of the "intact" sound being shorter than that of the detachment signal [1].

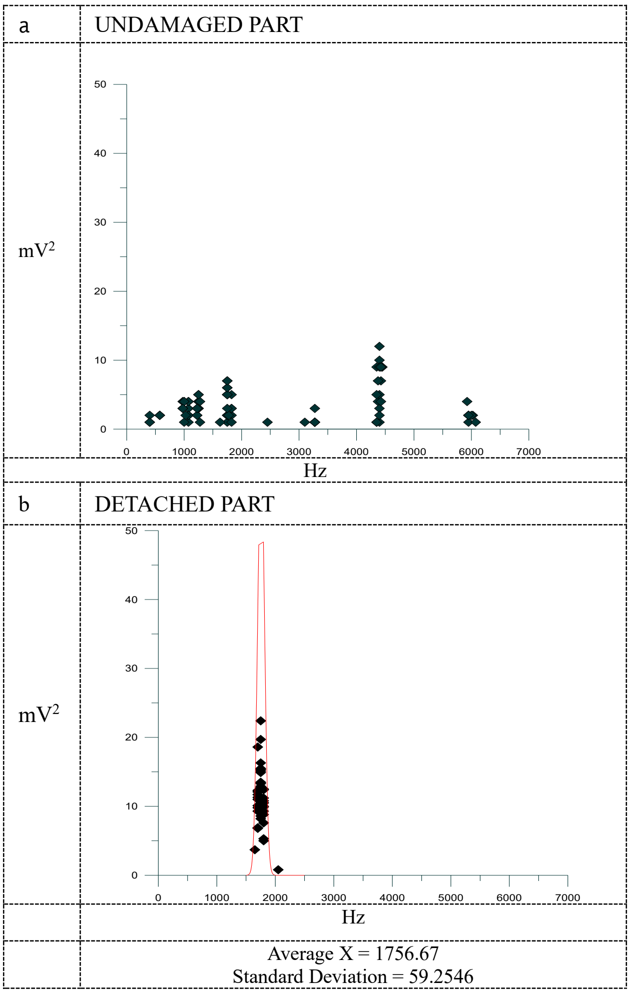

Fig. 2: Mockup showing plaster adhesion defects: a 100mm wide and 20mm deep detachment compared with the undamaged part.

The acoustical properties of a detachment between layers are influenced by the mechanical properties of the involved layers because sound is generated through the vibrations of the material itself. When a detachment occurs, it affects the transmission and propagation of sound waves within the material structure. Each layer within an artwork or artifact has its own unique mechanical characteristics. Apart from stiffness and inertia, several other factors influence the mechanical vibration of a surface. Considering these factors is essential when analyzing the mechanical vibration of surfaces, as they contribute to the overall behavior and response of the material to external stimuli.

From another perspective, detachments have the capacity to store potential energy similar to a spring, primarily due to the presence of air beneath the vibrating mortar layer. The air acts as a cushion, allowing for the storage of potential energy. Additionally, detachments acquire kinetic energy due to their mass. The depth at which the detachment is located influences the amount of kinetic energy acquired. A shallower or deeper position implies the presence of one or more vibrating layers above the air cushion, which affects the overall mass and, consequently, the amount of kinetic energy transferred to the detachment. By considering the potential and kinetic energy stored within detachments, we can gain insights into their behavior and understand their impact on the overall structural integrity of the object. This understanding is crucial for accurately assessing and addressing detachments in works of art or artifacts.

IV. APPLICATIONS OF THE PICUS SYSTEM COMPARED TO TRADITIONAL AUSCULTATION TECHNIQUES

Non-Destructive Evaluation (NDE) or destructive analyses can contribute to enhancing the overall understanding of artifacts. Methods of excitation can vary, for example, from acoustic to energetic, and the response detection methods can also vary, from acoustic FT observation to Hybrid Ultrasound Technique, from IR Imaging to Vibrometer Laser Doppler, and Speckle Interferometry.

However, the application of NDE techniques in the investigation of historical and artistic heritage faces certain limitations. Conducting measurements on-site is not always feasible due to various factors. These factors indeed introduce practical challenges and cost implications, leading to the less frequent use of advanced survey techniques in practical work environments. In such cases, conservator-restorers often rely on traditional auscultation techniques to analyze detachments. This specialized, handmade procedure involves lightly tapping the surface with the fingertips or knuckles of one hand and feeling the resulting vibrations with the palm of the other hand, as shown in Fig. 3.

The expertise and sensitivity of the conservator-restorer play a crucial role in this technique. The percussion is carefully calibrated based on the specific characteristics of the defect being assessed.

The tap is a brief, impulse-like force applied to the surface, and the operator strives to maintain a consistent force throughout the examination process. By closely observing and interpreting the vibrations and sounds produced during the tapping, the conservator-restorer gather valuable information about the condition and integrity of the surface or artwork.

Traditional auscultation techniques offer certain advantages in terms of accessibility, simplicity, and cost-effectiveness. They allow for direct physical interaction with the object, providing tactile feedback and a more immediate understanding of its condition. However, it is important to acknowledge that these techniques are subjective and rely on the skill and experience of the conservator-restorer. Therefore, the results may vary based on individual interpretation or if the analysis is conducted at different conditions (Fig. 4 a, b, c) and differ from the one provided with PICUS, which remains the same

Fig. 3: A Qajar glazed ceramic panel. The distribution of the detachments is evaluated using traditional auscultation technique.

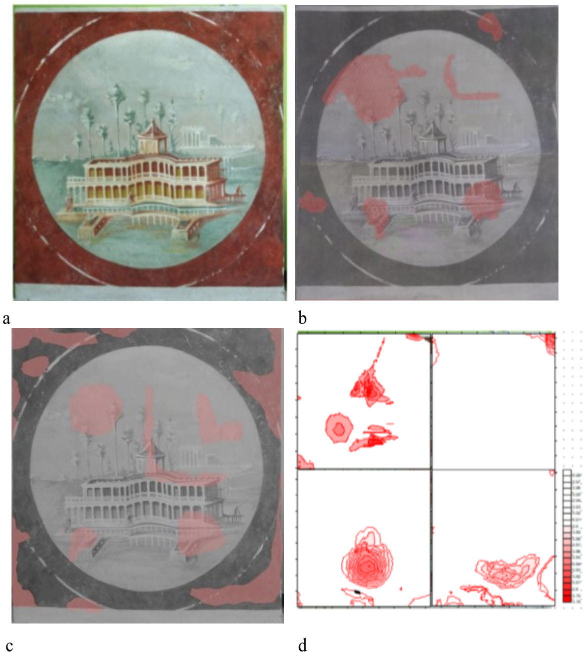

Fig. 4: a- wall painting 1 m^2 mockup; b, c- maps depicting the results of two different auscultation sessions conducted at different points in time; d- a detachment map provided by PICUS cross-correlation procedure

overtime (in Fig. 4 d).

V. EXAMPLES OF PICUS SYSTEM APPLICATIONS: SOUNDNESS OF AN UNCOATED ROMAN BRICK IN DRY AND WET CONDITIONS

For the sake of completeness, in addition to acoustically characterizing defects in regularly-shaped samples, efforts have been made to push the limits of the PICUS System on an irregularly-shaped object and in the search for discontinuities in brickwork, which represents the primary support for mural paintings from different eras.

In this case, the sample consists of a Roman "*semi-sesquipedalis*" brick (Fig. 5 a) obtained from a backfill site near a well-known Roman archaeological site. Due to its damage and irregular shape resulting from fractures and delamination along its short sides, the focus was on observing cohesion and density differences that could affect the material's soundness, the acoustic response to percussion with the PICUS probe; moreover, attention was directed towards establishing a color scale bias that could enhance the visualization of the irregular shape. The map (Fig. 5 b) is generated by processing the data using cross-correlation techniques between a reference point considered solid, well-fired, well-seasoned, and dry, and the points obtained from scanning the surface.

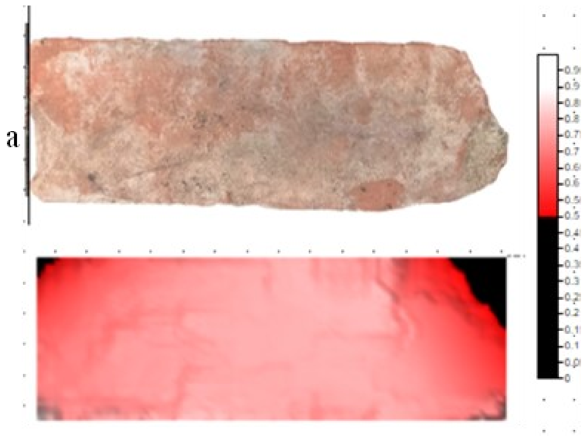

Fig. 5: a - dry Roman brick; b - map resulting from scanning the surface using the PICUS cross-correlation procedure, overlaying the base to determine the threshold at which cross-correlation index similarity can be considered.

To simulate another of the most common cases, which is that of waterlogged mural supports, the brick was vertically immersed in a few millimeters of water, which, through capillary action, rose to approximately one-third of its height.

The Power Spectrum graphs that follow in Fig. 6 illustrate the difference between the acoustic response of the dry brick and that of the wet brick (higher density), based on the frequencies emitted during percussion, with magnitude measured in mV2 and a frequency range

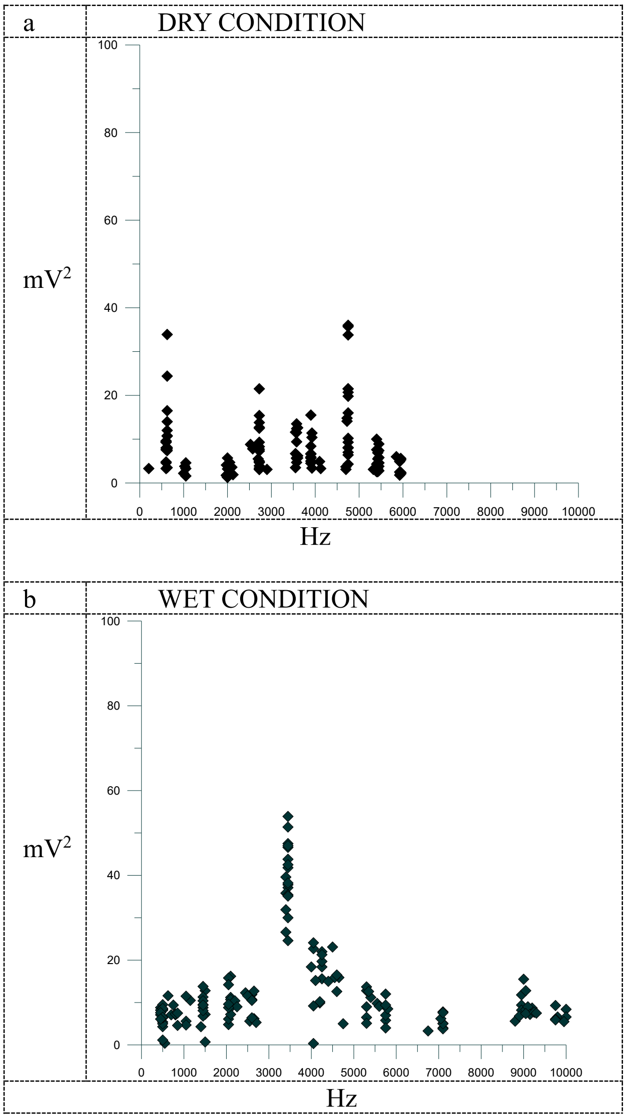

Fig. 6: a- the soundness of a dry brick; b- in the same portion of brick, now waterlogged, the power spectrum shows a different distribution, with a characteristic timbre at 3400 Hz.

varying from 0 to 10 kHz. In the wet support, a characteristic spectral component of the overall timbre map resulting from scanning the surface using the PICUS cross-correlation procedure, overlaying the base to determine the threshold at which cross-correlation index similarity can be considered.at 3400 Hz is present, which can also be discerned by the human ear.

VI. CONCLUSIONS

The PICUS system offers several advantages compared to traditional auscultation techniques.

Measurements and analysis conducted with this procedure can be digitally documented, facilitating record-keeping and data sharing.

We believe that a qualitative analysis of the surfaces (i.e. detached plasters or mosaics) to be assessed can be sufficient to obtain the necessary indication, in order to track evolutions of the defects and to design a stabilization intervention project, but on-going verification on site will provide a wider series of measurements to accurately establish the operating procedure of the PICUS.

Acknowledgement: The mockup in Fig. 1 is courtesy of P. Calicchia from the Institute of Marine Engineering, Research Unit Acoustics and Sensors "O.M. Corbino", Rome, Italy.

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