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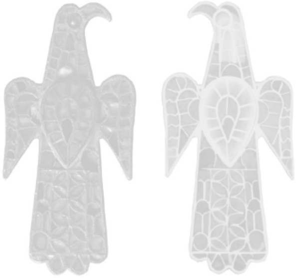

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USE OF THE PARAMETRIC LOUDSPEAKER IN ACOUSTIC DIAGNOSTICS OF PANEL PAINTINGS: LABORATORY CHARACTERIZATION AND ON SITE EXPERIMENTATIONS

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Abstract

The ACoustic Energy Absorption Diagnostic Device, ACEADD, reveals detachments of pictorial film in paintings. A transceiver unit delivers an acoustic wave towards the analysed surface, recording the incident and the reflected wave for the extrapolation of the surface impulse response and therefore of the absorption coefficient. A highly directive acoustic source was recently integrated in the measuring apparatus to overcome a limitation of the instrumental spatial resolution due to the geometrical spreading of the acoustic beam. The parametric loudspeaker generates audio frequencies in air by emitting ultrasonic waves, based on the nonlinear propagation of finite-amplitude waves, and unlike the traditional ones its directivity pattern is as narrow as the emitted ultrasonic waves.

Before integrating it into the measuring apparatus, a commercial parametric loudspeaker was characterized in an anechoic environment. The frequency response was measured using an omni-directional microphone aligned to the source's central axis. The aperture of the beam was identified by mapping the sound pressure level in the vertical half plane in front of the source. The analysed audio frequency band covered the significant interval of the acoustic excitation for revealing rather thin cavities beneath the pictorial film. The experimental - 3 dB aperture 2Θ resulted below 12° for most of the interesting frequencies.

The spatial resolution of the ACEADD system was tested on laboratory models. Moving the transceiver unit facing the model's surface, crossing both highly reflecting and absorbing materials, alternating acoustic responses resulted in a profile of the acoustic absorption indicator with rising or falling edges correlated to a spatial resolution of few centimetres.

Finally the instrument was used in field experimentations on panel paintings. The first investigation, on the *Annunciazione* by Benozzo Gozzoli, though restricted to two absorption profiles of major interest included an evaluation of the uncertainty of the measurement. A second investigation, on the *Venus and Mars* by Pieter Paul Rubens, was realized during usual museum exhibition time, providing an extended acoustic image of the panel.

The parametric loudspeaker showed a great potential in on site non destructive applications. Its small size, the beam directivity pattern, the non invasiveness gave evidences of great flexibility for moveable instrumentations, which can be easily used where the artefact is placed.

Introduction

Far from being only a traditional discipline, acoustics offers at present a great number of innovative technologies. Indeed the technological advancements in sonic and ultrasonic equipments have disclosed a huge potential in many useful applications, such as medical imaging diagnostics [1], materials characterization [2-3] and of course cultural heritage diagnostics [4-5]. In particular innovation in sound source technology and manufacturing gives to the applied acoustics field new opportunities for advanced methods and for modern approaches in non-destructive testing (NDT).

For this work, a last generation acoustic source has been selected, a commercial parametric acoustic array (PAA), and characterized in laboratory. Indeed this innovative source is a small sized transducer characterized by a very narrow directivity pattern, particularly interesting for on-site applications [6-7]. The tests aimed at the assessment of its suitability for the integration into a measuring system, the ACoustic Energy Absorption Diagnostic Device - ACEADD. The ACEADD is a non-invasive diagnostic method for revealing detachments of the pictorial film from the support in frescoes, ceramics and panel paintings. After a brief description of the acoustic imaging technique and the PAA operation principles, the sound emission properties of the acoustic source are analysed, i.e. the characteristic frequency band and the pressure field within 2 m from the transducer's surface. Once the PAA was integrated into the ACEADD system, the resulting properties of the apparatus were investigated in terms of spatial resolution. This aspect is fundamental for the consequent improvement of acoustic image quality by means of suitable image enhancement tools.

Finally in situ investigations are presented, where the improved configuration of the ACEADD acoustic imaging device is employed to analyse two panel paintings, the *Annunciazione* by Benozzo Gozzoli and the *Venus and Mars* by Pieter Paul Rubens.

The ACEADD diagnostic method

To extensively characterize complex and heterogeneous structures on site, an experimental method and the relative device were purposely implemented at the Institute of Acoustics and Sensors "O. M. Corbino" (CNR_IDASC). The method commonly provides images of multilayer structures where detachments may lie beneath the pictorial film. Acoustically speaking, a detachment is a sub-surface air cavity which behaves as a selective acoustic absorber, vibrating at specific frequencies when it is excited by an external pressure field. A representative physical model is a *mass - air spring* system, where the mass is concentrated in the superficial layer and the spring rigidity is that of the air volume in the cavity, whose fundamental resonance frequency depends on the density of air, on the surface layer's density and thickness and on the air cavity depth.

The method is based on the determination of the acoustic energy absorption coefficient, using a non-contact setup. The device automatically scans an area, while an acoustic source radiates towards the surface an acoustic wave with audible frequency content, a microphone records both the incident wave $p_i(t)$ and the reflected wave $p_r(t)$. By means of the Cepstrum algorithm, the impulse response $h_S(t-\tau)$ of the analysed target area is extracted, and both the reflection and absorption coefficients are calculated.

At a first level of analysis, for each i-th point, the results are expressed in terms of the total reflected energy Σ_i, operating an integration over a suitable time window W as wide as the value τ, and in terms of the absorbed energy percentage $ABS\%_i$ with respect to the most reflecting point over the entire analysed area

$$\Sigma_i = \int_W \left| h(t-\tau) \right|^2 dt, \qquad ABS\%_i = (\Sigma_R - \Sigma_i)/\Sigma_R. \qquad \text{(2a, 2b)}$$

For a deeper understanding of the deterioration degree a frequency analysis is required, where for each point the indicators are extracted as functions of frequency. This can provide an insight into many aspects regarding the conservation state of the artefact.

Finally, the technique provides acoustic absorption profiles or maps, localizing the defects where the absorption coefficient is considerably high. Further details about the technique and its development phases can be found in literature [6-7].

The Parametric Acoustic Array

The parametric acoustic array PAA generates audio frequencies in air by emitting ultrasonic waves, based on the nonlinear propagation of finite-amplitude waves, thus its directivity pattern is as narrow as the emitted ultrasonic waves. This property makes the PAA very attractive for its integration in the ACEADD measuring apparatus, to overcome a limitation of the instrumental spatial resolution due to the geometrical spreading of the acoustic beam. In the following paragraphs a brief description of the PAA functionality is provided, as well as the results of a laboratory characterization of the commercial parametric loudspeaker which has been integrated in the measuring system.

The theoretical physical principles of the parametric source are based on the study developed by Westervelt in 1963 regarding the nonlinear propagation of acoustic waves in air, and continued by other scientists in the following decades. The first sources were built as an array of ultrasonic transducers, with piezoelectric elements, which generated two primary frequencies f_1 and f_2 of appropriate amplitude [8-10].

The nonlinear interaction of two collimated primary beams induces a transfer of energy from the two primary frequencies to the higher harmonics and the sum and difference frequencies. In particular this interaction creates a virtual array of sources emitting coherently the difference frequency (the so called *end-fire array*). Subsequently this concept was extended by Berktay who extended the model and studied the self-interaction of the primary waves in nonlinear propagation regime introducing the *self-demodulation* of the parametric emission: a carrier primary frequency beam f_c with low audio frequency amplitude modulation, f_m, [11].

The most interesting features of PAA are the high directivity of the low-frequency beam, and the total absence of secondary lobes, figure 1(a). Furthermore, only the signal with the lowest frequency may persist at a certain distance from the transducer, while the primary frequency and the remaining higher harmonics are absorbed by the medium due to the higher absorption in air. It is therefore particularly suitable for a selective diffusion of sound.

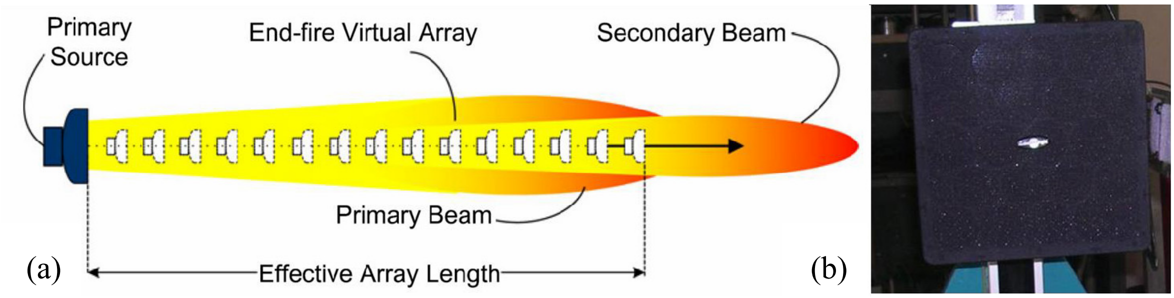

Figure 1. Physical principles of the Parametric Acoustic Array PAA functionality (a) [10], and the Holosonics HAS8 source integrated in the ACEADD system (b).

For our application the attention was focused on a commercial PAA, the Holosonics HAS8, shown in figure 1(b). The HAS8 is a square source of about 20 cm equipped with a control unit that delivers a composite signal to the transducer (carrier frequency f_c = 63 kHz) working in the self-demodulation regime; the control unit allows to regulate the output level and to balance the low frequency and high frequency content in the transmission response.

Characterization of the audio spotlight

Since the characterization of the HAS8 was oriented towards a general assessment of its applicability in NDT, the balance of low-frequency and high-frequency output level was regulated in order to obtain a curve as flat as possible. The HAS8 was studied in an anechoic environment. The HAS8 source was mounted at 1.1 m above the ground on a support, also equipped with an automated linear scan unit enabling vertical translation along the Y axis. A ¼ - inch free-field microphone (GRAS 40BE) with a nominal sensitivity of 4 mV/Pa was used in the measurements of the Sound Pressure Level *SPL*. The receiver was placed in front of the source aligned to its central axis (*Z* axis), at 90° with respect to it, and moved between 10 cm up to 8 m from the source.
In figure 2(a) the HAS8 frequency response at different distances is shown. In the frequency range from 2 kHz to 13 kHz, the measured *SPL* appears sufficient for the applications of our interest. Furthermore, the *SPL* value decays uniformly over the distance of 1 m. The low frequency levels are low at all distances, highlighting a limitation of the source, and for frequencies above 9 kHz the beam is formed beyond 10 cm.

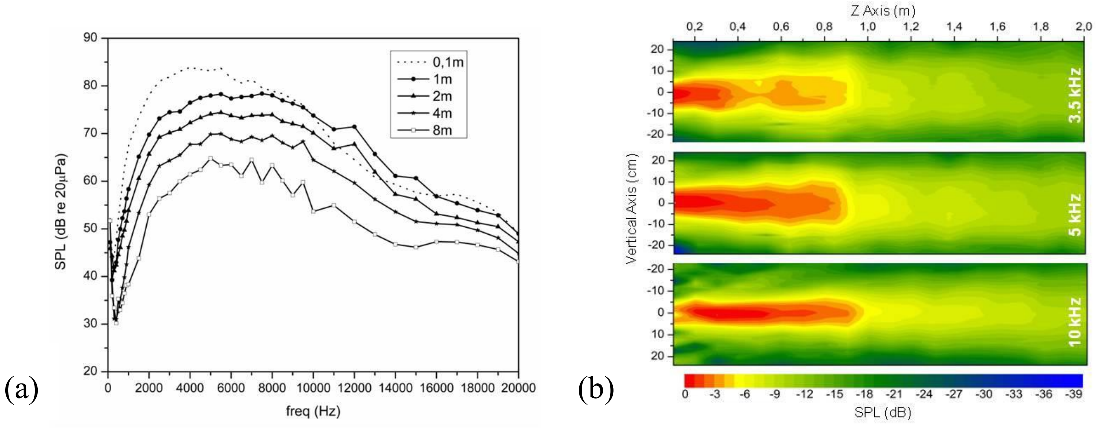

Figure 2. On axis *SPL* at different distances from the source HAS8 (a), and the characteristic pressure field in the *YZ* plane up to 2 m (b) [6].

The aperture of the beam was successively identified by mapping the sound pressure level in the vertical half plane *YZ* in front of the source. To this purpose three representative frequencies 3.5 kHz; 5 kHz; 10 kHz were analysed: the source was moved along the *Z*-axis while the microphone acquired vertical profiles in fixed positions every 10 cm, between 10 cm and 2 m from the source. This region crosses the characteristic near-field of the PAA where the virtual *end-fire array* determines the formation of the audio beam. In figure 2(b) the *SPL* maps in the *YZ* plane are shown as difference from the maximum value measured at the three frequencies. Each level of the colour scale corresponds to a decrease of -1 dB with respect to the maximum. It can be noted that as the frequency grows, the peak moves far from the source. Beyond the peak, as the distance increases, the pressure field is characterized only by the attenuation and beam slightly diverges. The experimental -3 dB aperture 2θ resulted below 12° for most of the interesting frequencies [6].

The spatial resolution

Once the HAS8 was integrated into the ACEADD system, the spatial resolution of this configuration was evaluated using the usual measuring procedure and setup (20 cm between source and microphone, and 30 cm between microphone and target surface).

Suitable laboratory models were used: in an Akustik®-Foam polyurethane panel, four square apertures with different size (±5 cm; ±10 cm; ±15 cm; ±20 cm) were made, and inside these apertures panels of closed-cell polystyrene were inserted, thus resulting in a sequence of materials having well defined opposite acoustic responses, shown in figure 3(a). Employing a wide band chirp signal (1 - 12) kHz, the total reflected energy Σ_i profiles obtained on the laboratory models indicate that the rising and falling edges are related to the spatial resolution of the instrument. In figure 3(b) these Σ_i profiles are normalized to the maximum value obtained on the reference material, an extended polystyrene surface, and compared with the rather uniform response of this reference material.

Only for the smaller aperture, where the peak does not reach the value obtained on the reference material, the amount of reflected energy is consistent with the reduced fraction of the acoustic beam contributing to the signal (between 1/4 and 1/3 of the beam section). Analysing the rising and falling edges, it can be stated that the transition from 10% to 90%, and vice versa, occurs in about 8 cm; the instrument starts to clearly perceive the effect of an area having different acoustic response at about 2 cm from the boundary.

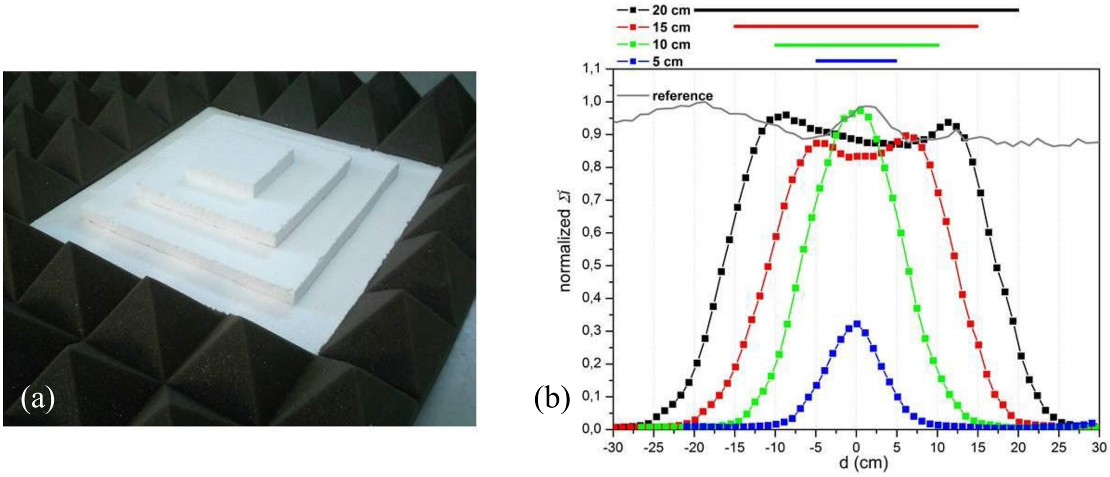

Figure 3. Laboratory models with apertures (a); total reflected energy profiles describing the response of alternating acoustic absorbers and reflectors (b).

In situ experimentation on panel paintings

When applying an acoustic pressure field to panel paintings, the properties of the wood support must be considered, since it greatly influences the experimental results and their interpretation. For this class of artefacts a preventive evaluation of the acoustic behaviour of the wood substrate is recommended, in order to discriminate its response from that of possible detachments of the pictorial film. The field experimentation on the two analysed panel paintings also disclosed unexpected potential of the ACEADD technique for the evaluation of the conservation state of the support.

Annunciazione by Benozzo Gozzoli (mid XV century A.C.)

An accurate restoration intervention of the renaissance *Annunciazione* was just completed when the acoustic measurements were carried out. Consequently, the amount of knowledge regarding the painting constituted the basis for the validation of the acoustic method on this class of artefact, although not exhaustive [6].

In the C.B.C. restoration laboratory in Perugia, the analysis was restricted to two absorption profiles of major interest; since it was the first application to panel paintings, it was preferred to concentrate the study on the evaluation of the uncertainty of measurement to a more extended analysis, in order to guarantee the significance of the results. The painting support is in poplar wood, 142 × 117 cm^2 with a thickness ranging among 2,2 cm and 2,5 cm. A chirp signal with high frequency content (4 – 15) kHz was selected, cutting off the characteristic vibration frequency of the substrate, to excite only possible delaminations of the painted layer. The two profiles (109 points, 1 cm step) along the longest side of the painting, identified as L1 and L2, were analysed: they cross the panel's junctions and different critic regions. The mean values from four repetitions were acquired for each profile, to account for the repeatability of the method and the heterogeneity of the acoustical response, thus providing the results with a known degree of accuracy.

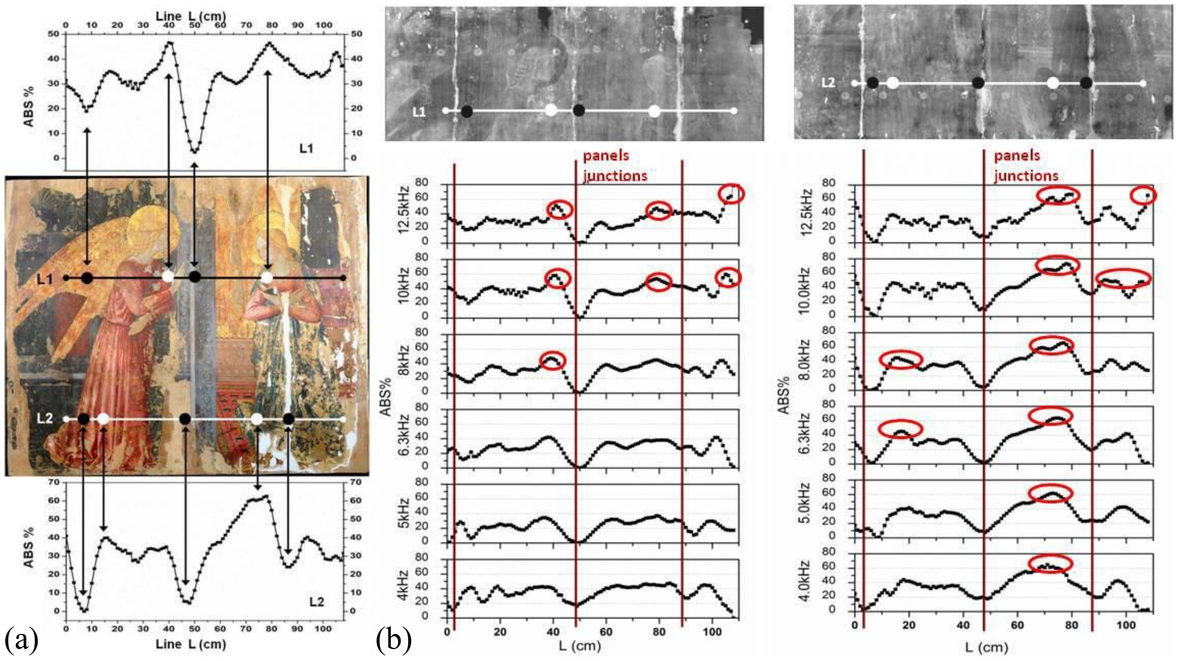

Figure 4. Absorption profiles L1 and L2 (a) with absorbing points (white) and reflecting points (black); frequency dependence of absorption profiles (b).

In agreement with the restorers' indication some areas, which underwent heavy consolidation work, still presented relevant absorption percentage, up to 47% for L1 and up to 63% for L2, in figure 4(a): this may indicate some residual effects of previous detachments, also due to the elastic properties of materials used for consolidation. The points where the indicator ABS% exceeds 40% localize few critical areas, even if related to a residual effect of consolidated detachments. In addition visible highly reflecting points lay near the panel's junctions, which means that also the status of the junctions might be evaluated. Actually this last thesis seems to be supported by the frequency analysis, in figure 4(b): studying the frequency dependence of the absorption profiles, it can be noted that absorption peaks are preferentially found in high frequency profiles related to thinner cavities. The lower frequency profiles do not present substantial absorption, except for the L2 profiles in the most damaged part of the painting, while the correspondence of the absorption minima with the panels junctions clearly emerges. This evidence suggests that the method may indicate the conservation state of the junctions as well, but this assumption needs to be verified by means of a wider experimentation.

Venus and Mars by Pieter Paul Rubens (1632 - 1635)

Venus and Mars is one of the major oil paintings of the remarkable collection of the *Strada Nuova Museums* in Genoa, hosted in *Palazzo Bianco Gallery*. The oak substrate measures 142 × 133 cm^2 and mean thickness 3.5 mm. The preparatory and the painted films are very thin as well. Furthermore, the painting presents the arrangement of the boards with opposite grain direction, denoting a high sensitivity to possible change of the environmental parameters. During the ages, the artefact underwent many restoration interventions both of the pictorial surface and of the rear support frame, as well as many changes in the microclimatic conditions. Only during the last decade the painting was hosted in a suitable location having a microclimate control system.

The diagnostic investigation aimed at identifying the current state of conservation after the last restoration intervention concluded in 1984. A chirp signal with high frequency content (4 – 16) kHz was selected, to avoid the excitation of normal modes of the support. Figure 5(a) shows the ACEADD system during in situ diagnostics in the museum; figure(b) (c) and (d) display the absorption maps obtained from the measuring system, covering a surface of 1,5 m^2 with 15207 points 1 cm apart. The results evidenced an overall good state of conservation, as expected due to the controlled microclimate, disclosing an interesting feature with an unexpected periodic structure. This light weakness, more evident in the upper part, can be related to the rear part frames, introduced in many successive restorations together with the changing of microclimatic conditions during the ages.

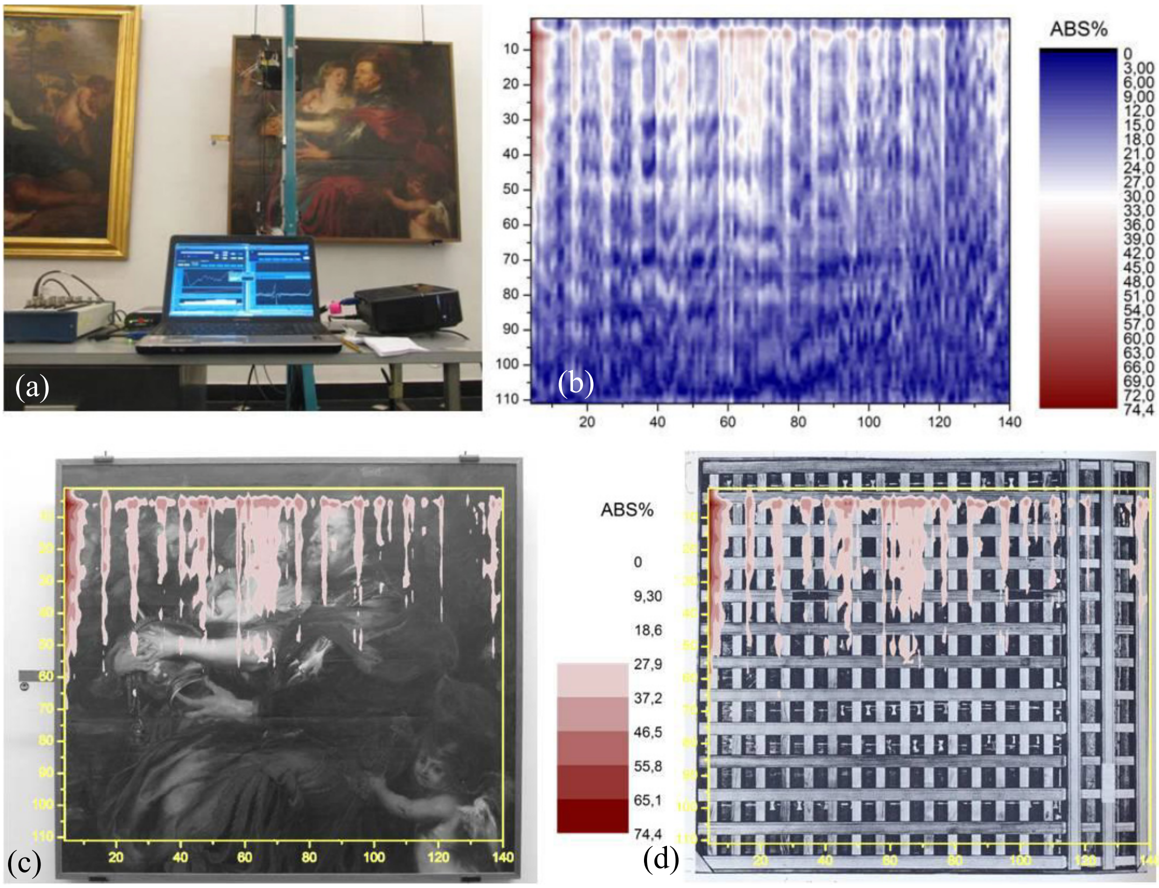

Figure 5. ACEADD system (a); acoustic absorption map (b); acoustic image on the painting's front surface (c) and on painting's back panel (d).

A deeper analysis of the cause inducing the above mentioned periodic structure is still in progress. An accurate estimate of the characteristic period will indicate if this effect is related to the current supporting frame or to a previous one: it is fundamental to understand if it depends on a direct, although unwanted, excitation of this rear structure or on the presence of delaminations left on the pictorial film by one of these supporting meshes that might had introduced additional constraints to the panel. A better understanding of this aspects will provide the key elements for a realistic interpretation of the experimental results.

Conclusion

The study of panel paintings must conjugate a suitable extension to cover wide surfaces and a high spatial resolution for small defect size. The PAA, integrated in the acoustic imaging system, showed a great potential in on site non-destructive applications thanks to its small size, to the high directivity, and to the great flexibility suitable for moveable instrumentations, which can be easily used where the artefact is placed.

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