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Exploring the potential of a frequency resolved acoustic imaging technique in panel painting diagnostics

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ABSTRACT

A new application of a contactless and low-cost acoustic imaging technique, for the diagnostics of the structural damage in panel paintings is presented. The artworks, exposed to a wide frequency band acoustic excitation, are analysed in terms of acoustic energy absorption coefficient in the audio frequency interval. The method reveals buried defects, such as detachments of the painted layer and flaws in the wood substrate, providing frequency resolved acoustic images. Three case studies are here discussed; the wood substrate configuration and the conservation state of the painted layer greatly differentiate the examined paintings. A collection of acoustic images is presented, highlighting a plurality of features characterized by different geometry and frequency response.

The study gives a representative visualization of the response of panel paintings to the acoustic excitation, suggesting a reliable usefulness of this technique in their safeguard. This knowledge base will orient the future validation on properly designed laboratory models.

1. Introduction

In panel paintings the peculiarity of the substrate, due to the hygroscopicity of the wood, and the great variety of configurations determine their high sensitivity to the environmental conditions. Effective diagnostic tools may highly benefit their preventive conservation. The development of innovative non-destructive techniques for a cost-effective and accurate evaluation of the structural damage may contribute to the actions for the safeguard. Specifically for problems related to the inner structure of panel paintings and the buried defects, some advanced methods were proved to be effective diagnostic tools, as described hereafter. The Air-Coupled Ultrasonic Imaging (ACUI) employs non contact transducers to propagate ultrasonic waves into the material, examining different areas while scanning the painting's surface. The method identifies the buried defects because they partially reflect back the propagating waves; typical devices operate in *reflection mode* analyzing the amplitude of the reflected wave and its delay time, or in *transmission mode* evaluating the amplitude attenuation of the transmitted wave crossing the material. This is a non invasive and high spatial resolution technique; but the speed of the raster scan and the complexity of the setup represent possible limiting factors [1,2]. The Laser Doppler Vibrometry (LDV) identifies the presence of detachments inducing their vibration while measuring the vibration velocity or displacement by means of a laser interferometer. Using a loudspeaker for the mechanical excitation, the technique becomes totally contactless [1]; the value of the vibration frequencies at resonance gives further information about the detached regions. Limiting factors are the cost and the accurate setup, requiring low environmental mechanical perturbations and specialized operators. The active Infrared Thermography (IRT) offers a great variety of approaches, among which the Pulsed Thermography (PT) induces sudden changes of the surface's temperature in response of flash-lamp excitation, thus limiting the exposure to light, and measures the successive temperature decay. This technique is used for mapping detachments but also for the inspection of the wood grain patterns [1]. The measuring procedures are relatively rapid also for extended surfaces, nevertheless complex data processing techniques are commonly used off line. Optical techniques are widely used in conservation science due to their non-invasiveness and to the high spatial resolution. In particular optical coherent techniques, employing laser light sources, are more recent and provide high quality images. For instance, the Holographic Interferometry (HI) reveals defects at an early stage, material discontinuities and areas of excessive mechanical stress mapping the patterns of fringes, and their deformation, obtained by the superposition of two holograms. These features are enhanced in

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Abbreviations: AF-AI, audio frequency acoustic imaging; ACEADD, acoustic energy absorption diagnostic device; IAI, integrated acoustic image; FRAI, frequency resolved acoustic image

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thermal drift mode, when a short thermal irradiation induces little deformations in the object under exam [3,4]. The Electronic Speckle Pattern Interferometry (ESPI) presents a lower image quality, but it is suitable for on site investigations with portable instruments working in context characterized by environmental perturbations. A recent Digital Speckle Pattern Interferometer (DSPI) was applied to reveal the panel painting's structure deformations, caused by environmental thermo-hygrometric fluctuations, by recording a sequence of interferograms at a very high frame rate, and analyzing them off line [5]. Often the cost and the complexity of the operational procedures, the need for specialized operators in the data analysis and interpretation limit the use of these advanced techniques in the conservation practice.

The present work examines the information obtained by means of a relatively low-cost acoustic technique in the new application to panel paintings diagnostics. The audio frequency acoustic imaging method (AF-AI) and the relative instrument, named Acoustic Energy Absorption Diagnostic Device (ACEADD), were conceived and patented for the contactless measurement of the acoustic absorption coefficient on extended surfaces exposed to acoustic wave excitation, providing their acoustic images. A composite experimental activity, encompassing laboratory tests and on site investigations, has evidenced that the AF-AI method can reveal some forms of structural damage in multilayer structures, such as different types of paintings, although for each class of artifacts a peculiar acoustic response emerges and the research is at different phases. In all cases a similar approach based on solid metrological principles has been adopted including: laboratory validation on artificial models and field experimentation; a specific data analysis; the interpretation of the resulting images; the comparison with other methodologies.

The initial laboratory validation demonstrated the correct localization of artificial detachments on fresco models, whilst the successive tests on real frescoes evidenced a good agreement of the resulting acoustic images with the traditional restorers' inspection [7], and with IR thermographs under particular conditions [8], i.e. when employing acoustic waves with specific frequency bands as excitation source.

The method was successfully extended to painted surfaces of different types. In experimentations on panels of glazed ceramic tiles, the potential of the method was explored for detecting the tile/mortar adhesion failure and the delamination of the glazed layer from the clay substrate [9]; laboratory validation has recently been undertaken using suitable models with artificial delaminations [10].

Only in recent times the technique was further applied to panel paintings, after the integration of an innovative and highly directional acoustic source, useful for improving the spatial resolution and enhancing the sensitivity of the device to small defects. The first study on a panel painting, although restricted to two narrow regions, disclosed interesting results suggesting the possibility to evaluate the conservation state of the substrate and that of the painted layer [11].

Some challenging issues in this field are related to the multiplicity of the decay processes that can merge together, contributing to the overall conservation state of these artworks. Specifically, the detachment of the painted film or of the preparatory layer from the substrate; the presence of flaws in the wood substrate; the failure of the adhesion at the junction of wood axes; the possible constraints introduced by the cradles; the attack by xylophagous insects causing the decrease of the wood density.

The aim of the present investigation is to explore the potential of the AF-AI diagnostic method to: i) give helpful indications about the conservation state of panel paintings; ii) to discriminate different damages, analyzing the features of a set of acoustic images displaying the data in different frequency bands; iii) analyse the peculiar acoustic response from different panel paintings, for orienting the construction of proper models for the future laboratory validation.

The paper provides a brief overview of the acoustic imaging technique in Section 2, dealing with the most relevant aspects related to the acoustic energy absorption evaluation and the extraction of the frequency resolved acoustic images in Section 2.1, and to the measuring procedure in Section 2.2. The three panel paintings, constituting the materials of the present investigation, are separately illustrated in Section 3, together with the first collection of acoustic images in the audio frequency range (1–16 kHz) obtained for this type of artwork. Finally, the discussion in Section 4 will gather the evidences emerging from the comparison of the results of the three case studies, aiming at a better understanding of the differences and the similarities found in the acoustic images.

2. Method and device

The AF-AI diagnostic method investigates the complex and heterogeneous structure of paintings, mapping different forms of damage. One of the most frequent damage is related to the presence of detachments between the painted layer and the preparatory layer, or between this last and the substrate. A detachment is a sub-surface air cavity resonating at specific frequencies when it is excited by an external acoustic pressure field. A physical model that simply describes a detachment is the mass – air spring system, where the mass M is concentrated in the superficial painted layer having extension S, and the spring rigidity k_{air} of the air volume V_0 inside the cavity is expressed in Eq. (1) [12]

$$k_{air} = \frac{c_0^2\rho_0}{V_0}S^2 = \frac{c_0^2\rho_0}{d}S \tag{1}$$

with c_0 being the sound velocity in air (343 m s^{-1} at 20 °C), ρ_0 the density of air (1.292 kg m^{-3}), and d indicating the air cavity thickness. As described in Eq. (2), the fundamental resonance of this system occurs at

$$f_0 = (1/2\pi)\sqrt{k_{air}/M} = (c_0/2\pi)\sqrt{\rho_0/(\rho_S td)} \tag{2}$$

where ρ_s and t are respectively the density and the thickness of the surface layer. A detachment excited by an external acoustic pressure field behaves as an acoustic absorber, known as Helmholtz resonator, absorbing the acoustic energy most efficiently in a relatively narrow band of frequencies near its resonance [12].

Other mechanisms are also relevant, for instance the acoustic absorption due to the material's porosity. In panel paintings the wood substrate affected by the attack of xylophagous insects presents a decreased density and an enhanced porosity. In porous materials, characterized by networks of interconnetted pores, viscous losses convert acoustic energy into heat. Such materials absorb relatively small amount of acoustic energy at the lower frequencies while they become efficient absorbers at relatively high frequencies, for instance above about 500 Hz for most architectural materials. Thus the absorptivities of porous materials strongly increase with increasing frequency, but also with increasing material thickness [12].

The AF-AI method correlates the significant amount of acoustic energy absorption, in the audio frequency interval, to the presence of damages in the painting under investigation. Assuming that an acoustic source radiates an acoustic wave towards a painting's surface, a microphone placed between the source and the analysed surface can records both the incident pressure wave $p_i(t)$ and the wave reflected back by the surface $p_r(t)$, detected with a delay time τ due to the longer path the reflected wave travels. These two constitute the composite pressure signal $p(t)$, given in Eq. (3)

$$p(t) = p_i(t) + p_r(t) = p_i(t) + L_b p_i(t) \otimes h(t-\tau) \tag{3}$$

where L_b is a geometrical factor accounting for the beam spreading and the different paths between the incident and the reflected waves, and $h(t\text{-}\tau)$ is the impulse response of the surface under investigation. Analysed in the frequency domain, $p(t)$ turns into the following Eq. (4)

$$P(f) = P_i(f) + P_r(f) = P_i(f) + L_b P_i(f)H(f)e^{-i2\pi f\tau} \tag{4}$$