Characterization of a parametric loudspeaker and its application in NDT

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The parametric loudspeaker combines the high directivity at the audio frequencies with the small size of the transducer, thanks to the nonlinear interaction of finite-amplitude ultrasonic waves. These properties make this class of sources an attractive investigation tool especially for non destructive testing (NDT). Till now the research has been mainly focused on the optimization of the transducer and the signal pre-processing, while only recently actual applications mainly in the field of material's acoustical characterization are emerging. The authors present the analysis of the pressure field generated by a commercial parametric loudspeaker integrated in a system purposely developed for acoustic diagnostics on objects of heritage interest. It was used in an investigation on the renaissance panel painting Annunciazione by the Italian artist Benozzo Gozzoli (XV century) revealing pictorial film detachments. Preliminary results are here presented, disclosing the potential of the parametric loudspeaker for the enhancement of the spatial resolution in the acoustic measurement, of the non invasiveness of the investigation tool, and also of the operator comfort.

1. Introduction

In air-borne acoustic measurements traditional loudspeakers are commonly used as excitation source. But new generation sound sources, developed in recent years, need to be taken into account in laboratory and in situ measurements, also considering that some of them are easily available on the market. Some innovative products present particularly attractive features, which make their employment in acoustic metrology and in Non Destructive Testing (NDT) worthwhile to be investigated. Under this point of view, the authors believe that in particular the parametric loudspeaker represents an interesting tool for many acoustical applications mainly due to its peculiar directivity pattern combined to the small transducer's size.

The present work deals with the characterization of the pressure field of a commercial parametric loudspeaker and the use of this highly directive sound source in an application for non destructive acoustic diagnostics of an antique panel painting. Actually, the narrow acoustic beam-spot offers clear advantages with respect to traditional loudspeakers, as far as spatial resolution is concerned. The transducer employed in the study is characterized by a very small custom size, particularly suitable for in situ acoustic investigations; it was integrated in a measuring system denominated Acoustic Energy Absorption Diagnostic Device (ACEADD) and used to reveal the pictorial film detachments on the XV century *Annunciazione* by the Italian renaissance artist Benozzo Gozzoli.

The parametric loudspeaker characterization was realized at the Institute of Acoustics and Sensors of C.N.R. (IDASC_CNR), while the in situ measurement on the painting was carried out at the C.B.C. restoration laboratory in Perugia (Italy), where the Annunciazione was for few years stored, undergoing an accurate restoration intervention.

2. Parametric Loudspeaker Characterization

The Holosonics Audio Spotlight AS8 is a square source of about 20 cm side, working in the self-demodulation regime. Its control unit, which is a processor and an amplifier, can be fed with an audio input signal, in the same way as traditional speakers, and provides to the transducer a 63 kHz carrier frequency with the proper amplitude modulation deriving from the original input signal. The envelope function which provides the amplitude modulation contains also the corrections needed to prevent from audio wave distortion. The AS8 control unit allows to regulate the output level and to balance the low frequency and high frequency content in the frequency response.

The characterization of the source was firstly carried out selecting the setting used in the application, the measurements were performed in a semi-anechoic room at the IDASC_CNR. The AS8 source was mounted at 1.1 m above the ground on a support equipped with an automated linear scan unit enabling vertical translation along the Y axis. An omni-directional microphone, with frequency response between 50 Hz and 15kHz and sensitivity - 42 dB re 1 V/Pa, was used in the measurements. 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 2 m from the source. A National Instruments 16 bit multifunction data acquisition board was used to generate the audio input signal sent to the loudspeaker and to record the pressure at the microphone. A custom software utility was employed to control the data acquisition board together with the linear scan unit. The calibration of the microphone, the ambient noise monitoring and an initial regulation of the source setting completed the preliminary tests in the measuring procedure. The ambient parameters were constantly monitored, and the ambient noise was always less that 20 dB re 20 μPa.

Initially the AS8 characteristic frequency response was identified by measuring the SPL at different distances from the source along its central axis, verifying how the frequency response modifies with distance. Pure tones in the 4 kHz ÷ 15 kHz band were used, and the acquired signals were filtered by a one-third octave-band filter.

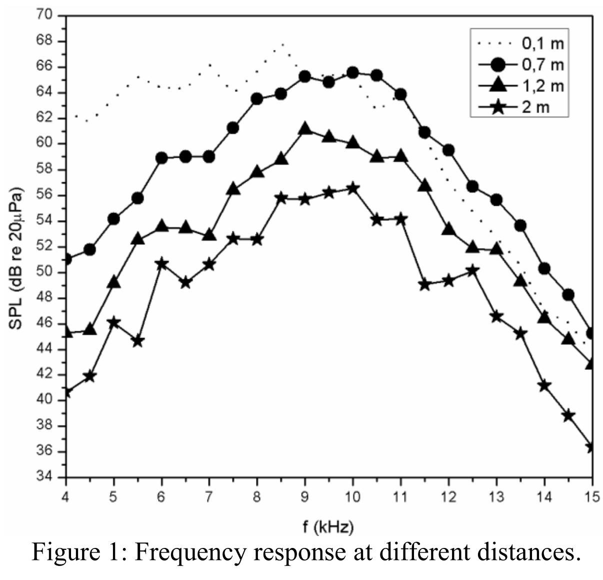

Figure 1: Frequency response at different distances.

In Figure 1 the AS8 frequency response, relative to the selected setting, is reported for different distances. The analyzed portion of frequency band was purposely restricted to the above mentioned interval; indeed this represents the significant frequency content of the acoustic excitation for the specific application, i.e. for revealing thin cavities beneath the pictorial film in the painting. While the extension of the analyzed portion of the pressure field contains the typical working distances used in the specific application.

The curves show that for frequencies lower than 9 kHz the beam at 10 cm is not yet properly formed, while all the frequencies are equally decaying beyond 0.7 m.

In order to verify the size of the acoustic spotlight, the points at 3 dB below the pressure field maximum were identified and displayed in Table 1. They delineate the progressively growing beam at the two characteristic working distances of the NDT application described in this work. At about 0.7 m the beam width is roughly between 30 cm and 10 cm, depending on the frequency value, while ad 1.2 cm is between 26 cm and 11 cm.

The beam aperture has been reported for the most significant frequencies in the investigated interval.

Table 1: Angle at -3dB for different frequency values at 70 cm and 120 cm

	4 kHz	8 kHz	10 kHz	13 kHz	15 kHz
$\vartheta^{+}_{-3dB}(70_{cm})$	14°	7°	4°	4°	3°
$\vartheta^{-}_{-3dB}(70_{cm})$	-14°	-7°	-5°	-5°	-3°
$\vartheta^{+}_{-3dB}(120_{cm})$	-	8°	6°	3°	3°
$\vartheta^{-}_{-3dB}(120_{cm})$	-	-6°	-7°	-3°	-3°

3. ND diagnostics on antique paintings

The acoustic method, ACEADD, reveals sub-surface air cavities in multilayer structures of heritage interest such as frescoes.

Developed and patented at the IDASC_CNR in 1999, the ACEADD method was initially validated on laboratory models containing artificial detachments [1,2]. This laboratory test showed that the technique is able to correctly localize the cavities measuring the acoustic energy absorption coefficient of the surface under study, and it identifies some detachment's geometrical characteristics by analysing the absorption coefficient in the frequency domain. After laboratory validation the method was applied to real frescoes, giving evidence to a good correspondence of the experimental results with the restorers' inspection [3]. Successively the range of application of the ACEADD method was widened studying the acoustic response of other multilayer structures such as glazed ceramic tiles [4], and recently that of panel painting [5]. The ACEADD method was recently compared with IR Thermography in a study realized on the same portion of wall paintings, whose results indicated a good correspondence between the two techniques when the acoustic method uses an excitation signal in the 4 kHz – 20 kHz frequency band, while a better agreement of the acoustic method with the restorers inspection emerged when using an excitation signal in the 100 Hz – 12 kHz frequency band [6].

From the acoustical point of view an air cavity behaves as a selective acoustic absorber vibrating at specific frequencies, when it is excited by an external pressure field, thus being identified through acoustic energy absorption phenomena. The method is based on the evaluation of the acoustic absorption process occurring in a detached portion of a fresco. Hidden cavities within walls (detachments) are excited by means of a sound wave and the acoustic energy absorption coefficient, that fraction of energy not reflected back by the surface, is properly measured. In this condition, a detachment vibrates at specific frequencies, related to its thickness, thus absorbing the acoustic energy, while a rigid wall reflects back all the incident energy. The acoustic imaging experimental apparatus includes a transceiver unit and its circuitry, a scan unit, a data acquisition, data processing, and motion control unit with standard hardware components and a purposely developed software component. Employing a non contact setup, the equipment automatically scans an area, radiating towards the surface an acoustic wave with audible frequency content and recording both the incident and the reflected waves. A suitable signal processing, based on the Cepstrum algorithm [1,2], extracts the impulse response of the analyzed surface and, after Fourier Transform, the related absorption coefficient. An acoustic image of the analyzed area is finally provided, localizing the defects where the absorption coefficient is high. The measurements can be carried out using an excitation sound wave with different frequency content ranging in the 100 Hz – 20 kHz frequency band and different step size between adjoining points from few centimetres down to 1 cm, thus enhancing the sensitivity of the method to size defects.

Measuring the acoustic impulse response, $h(t - \tau)$ with τ being the delay time of the reflected wave, in equally spaced points of the surface under investigation, a critical step is represented by its extraction from the cepstral trace by means of a proper window function [1,2]. The duration of this time window determines the lower cut-off frequency in the absorption coefficient. If scattering elements are present close to the investigated area, spurious reflection peaks may occur inside the time window, impairing the correct impulse response extraction. The use of a highly directive sound source limits the problems arising from this situation. For the i-th point the following two indicators are extracted:

$$\Sigma_i = \int_{\mathrm{TimeWin}} \left|h(t-\tau)\right|^2 dt \qquad (1)$$

the amount of total reflected energy Σ_i, and the absorption percentage $ABS\%_i$

$$ABS\%_i = (\Sigma_R - \Sigma_i)/\Sigma_R \qquad (2)$$

with respect to the most reflecting point indicated by the subscript R.

4. Results

In this investigation the transceiver unit of the diagnostic device, shown in Figure 2, is composed of a Holosonics AS8 Audio Spotlight and a miniature omni-directional microphone, in coaxial configuration. The use of the audio spotlight allows to irradiate a smaller portion of the painted surface than the traditional sound sources usually do. A National Instruments 16 bit multifunction data acquisition board generates the audio input signal sent to the parametric loudspeaker, with a frequency band containing the expected resonance frequencies of the defects under investigation, and records the pressure at the microphone. The AS8 source was mounted at 0.7 m from the microphone and placed at 1.2 m from the painted surface, and was fed with a sine wave sweep audio modulation in the 4 ÷ 15 kHz frequency band.

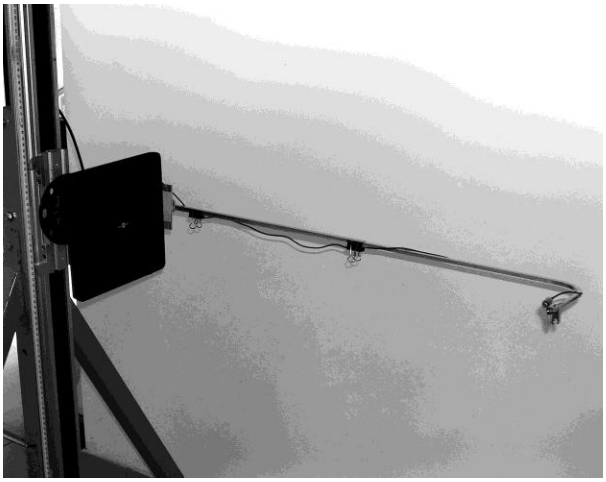

Figure 2: Transceiver unit.

The possible resonances of the wood substratum, estimated at lower frequencies, were discarded by the selected frequency band, which is appropriate to excite thin cavities beneath the pictorial film. Initially the proper output level was regulated, the frequency response in the frequency range of interest was measured, and the geometrical spreading of the incident wave was evaluated (this last parameter influences the impulse response extraction). The results of these initial tests are part of the system calibration procedure. Furthermore a beam spot on the panel of 30 cm in diameter resulted as maximum width for the selected frequency band.

Two profiles, identified as L1 and L2, running parallel to the longest side of the panel painting were analysed: they perpendicularly cross the three panel junctions and different critic regions. For each profile 109 points, 1 cm apart, were collected and mean values from four repetitions were calculated, in order to account for the repeatability of the method and the heterogeneity of the acoustical response. Figure 3 shows the image of the painting with the variation of absorption percentage, with respect to the most reflecting point of the profiles taken as reference point.

The absorption coefficient of this reference point was also compared to a large set of curves measured on a rather uniform reflecting wall in laboratory, in order to identify the dispersion values of the absorption indicator, Σ_i, which represents the limit for homogeneity. A 5% relative standard deviation of the indicator Σ_i, obtained in laboratory, provides the limit for which the acoustic responses from different points are considered uniform.

The analysis of the values of the same indicator, obtained on the panel painting, indicates a higher dispersion than the uniformity limit: the relative standard deviation in this case reaches 14% for L1 profile and 22% for L2 profile, denoting a noticeable but still not relevant degree of heterogeneity in both profiles.

In terms of absorption percentage ABS%, the experimental data indicate that percentages up to 47% appear in L1 profile, while percentages as high as 63% are achieved in L2 profile. These values assume a clearer significance when compared with the percentage of 25%, obtained in laboratory on the uniform reflecting wall taken as reference surface. An overall low absorption phenomena along the two profiles can be assessed, more evident in L2 profile. Furthermore, in previous studies it was found by the authors that absorption percentage below 30% means regular variation of the acoustic response in an undamaged artefact. In Figure 3 the positions of the most absorbing areas and the most reflecting ones are reported on the painting image by means of white and black points respectively. Only few regions show an uneven behaviour: a well delimited area in L2 profile between the left end of the Virgin's mantle and the carpet presents the most consistent absorption; a farther region on the Angel's mantle and two smaller regions in L1 profile, near the Virgin's neck and the Angel's hand respectively, present medium level absorption. Indeed, these regions represented the most damaged areas which underwent a deep and complex restoration process; thus the residual absorption found may be related to a still present fragility of these parts.

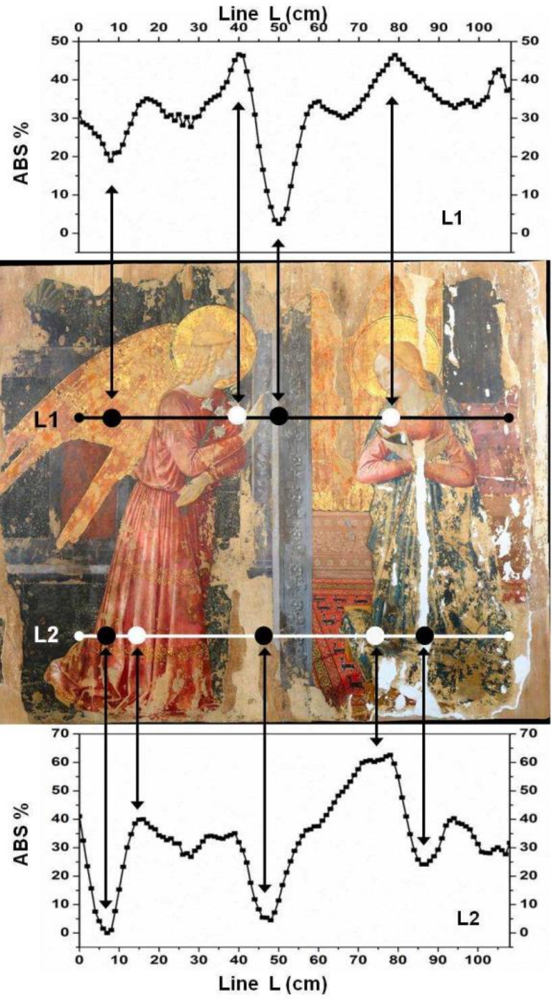

Figure 3: The two profiles on the painting's image with relevant absorbing areas (white points) and highly reflecting areas (black points).

Since the measurements were carried out after restoration, the presence of absorbing areas may also be ascribed to the elastic properties of the materials used for consolidation. Unfortunately no measurement was realized on the Annunciazione before restoration, so that no objective improvement in the acoustic behaviour of these critical regions can be assessed.

Another important feature emerging from data regards the recursive occurrence of absorption minima, or equivalently high reflecting points, mainly located in the central and two lateral parts of the panel, appearing in both profiles, those marked with black points. Figure 4 reports the superposition of the two profiles with both the absorbing and the reflecting points on the painting's radiograph; this last allows to highlight some details, not visible in the painting image, such as the artist's technique, different pigments, and underpaintings as well as the underlying support's characteristics. From this superposition the correspondence of the most reflecting areas (black points) with the panel's junctions clearly appears in five of the six crossings, while the difference among these minima suggests that the degree of deterioration of the junctions may also be revealed.

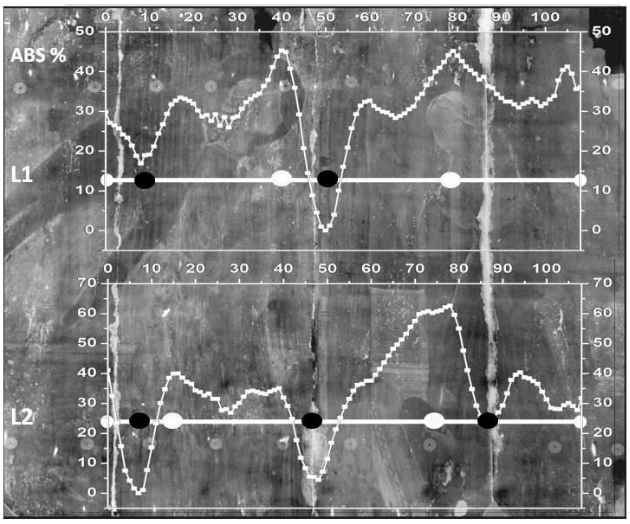

Figure 4: The two profiles on the X-ray image of the panel painting with relevant absorbing points (white) and highly reflecting points (black).

This outcome leads to the hypothesis that the experimental method offers a view of the state of the junctions as well as of the painted layer. The high acoustic reflection in the vicinity of the aforementioned junctions may be due to the presence of materials used to secure the timber panels together, thus imparting to the surrounding region a high rigidity which prevents it from vibrating under the action of an external pressure field. It can therefore be thought that the experimental method is able to detect the state of deterioration of the junctions, due to the deterioration and loss of the ligands and a poor adhesion between the panels. This state can therefore be detected by the presence of an abnormal absorption. It is emphasized that these considerations should be supported by further experimental investigations. A possible discrimination between the state of a junction and that of the overlying paint layer leads to the frequency analysis of the absorption coefficient, which is beyond the scope of the present paper.

5. Conclusion

First results of a particular NDT application to heritage objects with the use of a parametric source have been presented. The method, developed at CNR-IDASC and commonly used with linear acoustic sources, has been successfully applied with a commercial parametric loudspeaker, the AS8 by Holosonics. Actually, this kind of source represents a relatively cheap and easy solution for the integration in measuring system. Preliminary parametric loudspeaker's characterization showed that best results are obtainable in the range of (2 - 13) kHz which matches quite well with the frequency interval of interest for the proposed diagnostic method of heritage objects. The high directivity of the parametric loudspeaker offers some advantages: the scattering from the borders is reduced so that wider areas can be analyzed, preventing the occurrence of spurious reflection peaks close to the principal one; the spatial resolution is enhanced allowing finer details to emerge; the characteristic absence of side lobs offers to the operators a comfortable working environment.

Acknowledgments

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