A non-destructive, contactless technique for the health monitoring of ancient frescoes.

A non-destructive, contactless technique for the health monitoring of ancient frescoes

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ABSTRACT. In this paper an innovative non-destructive, contactless technique applied to the health monitoring of ancient frescoes is presented. The problem of the health monitoring of artistic frescoes without a direct interaction with structures and paintings is of great concern in the field of art restoration and preservation. In artistic frescoes, the partial detachment of plaster portions is a typical and serious problem. Both layer-to-layer detachments and delaminations and surface cracks are usually present in ancient wall paintings. At present, the standard procedure of diagnosis consists of manual inspection, but produces only approximate information. This paper describes an acoustic, non-invasive, experimental technique of diagnosis, based on the acoustic-structural interaction which occurs when a fresco wall is excited by a loudspeaker. The analysis of the acoustic pressure field and of its alterations allows the assessment of detachments, since the acoustic modal parameters are affected by the acoustic system boundary conditions, i.e. the portion of analyzed fresco. The reconstruction of the modal behavior of the analyzed portion of the fresco is made by a scanning laser Doppler which measure the velocity field of the observed surface. It is a non-contact measure technique that provides a great accuracy. Experiments carried out on fresco artificial specimens show the potential of the technique.

Keywords: NDT, frequency-based identification method, fresco health monitoring.

INTRODUCTION

1.1 Typical fresco structure and causes of deterioration. The fresco is the most widespread traditional technique of wall decoration. Its application has known few variations in the centuries and has remained unchanged since today. The fresco painting technique is born in remote times before the *Buon Fresco* of the Italian Renaissance. It needs the use of pigments to base of colored sands or metallic oxides, able to withstand the discoloring effect of the mortar. The shades are simply dissolved in water, or in water of mortar or diluted *grassello*, and smoothed against plates of marble to eliminate all the lumps or coarse parts, [1].

The preparation of the wall for the fresco typically implies the realization of a plaster made of many layers: the first layer is called *rinzaffo*, it is composed of mortar, sand and brick crocks in ratio 1:2:1, and it has the function to stick to the supporting wall and carry the following layers. The intermediate layer is called *arricciato*; it is realized with mortar and river sand (ratio 1:2) and has a leveling function. The finishing layer has mainly an aesthetic function, and is realized in mortar and dust of marble thin (1:2). The finishing layer must be applied only in the amount that can be painted during a day of work, since the color is given in mixed together with the mortar layer when still fresh (from here the name fresco) and under curing. The pigments are incorporated in the carbonate crystals that are formed after the chemical hardening reaction, and give a bright and transparent color to the treated support, [1].

Antique frescoes are affected by particular environmental factors (variations of temperature and moisture), pollutants (superficial deposits of dirt, biodeteriogens and chemical attacks) and physical (building structure subsidence, seismic vibrations). These factors can bring surfaces to different degrade pathologies: delamination, salty efflorescences, sub-efflorescences, separations, stains, pulverization, [2]. Particularly, the pathologies from separation as detachments, stains, sub-efflorescences bring to a lack of adherence located within the support layers behind the pictorial film. The presence of air, moisture and salts between the layers can bring to the separation and fall of plaster and fresco layers. For example, figure 1 shows a detail of a sixteenth-century fresco in the *Cappella del Comune* at the Dome of Parma (picture taken by the authors in year 2008), where can be noticed, inside the outlined red zone, a wide separation of the *arriccio*, that has locally caused the complete loss of the fresco, here highlighted by the green line.

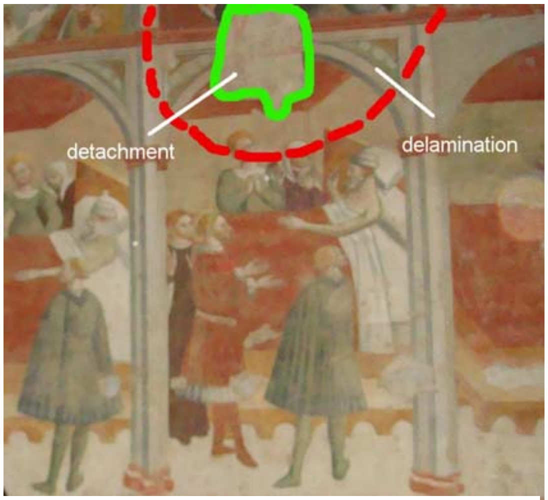

Figure 1. Ancient fresco of the *Cappella del Comune* at the Parma Dome.

1.2 Diagnostic methods for frescoes. Although analytical methodologies and techniques for detecting the chemical-physical characteristics of works of art are already known and used since a long time, very often it is made reference to the manual skill of the restorer. After a visual and manual inspection, he is generally able to judge the health of the work. The base idea of the techniques for non-destructive (ND) non-invasive (NI) diagnosis is to replace the human senses with measuring tools, in order to automate, standardize and speed up the procedures. Some fundamental characteristics are expected from these methodologies of investigation: no remarkable measurement intrusion; remote measurements possibly without physical contact; ample frequency response; high sensibility; digital recording of data; instruments portability.

A monitoring techniques family is based on the vibration of the fresco: a classical example is the *impact test*, in which the surface of the fresco is struck with a small instrumented hammer able to measure the intensity of the impulse, and the state of maintenance of the fresco is deduced on the basis of surface vibration velocity, by analyzing the mobility differences due to local damages. For smaller works of art, it is possible to use standardized means of investigation, for example X-rays. This introduces nevertheless other limitations, due to the necessity to move the work from its usual location and hence not generally applicable. Another very common test is thermography, that consists in the measure of the surface temperature distribution of a material after a thermal impulse. Anomalies in such distribution are clue of a possible defectology. Other less diffused methods are based on ultrasounds, interferometry or radar prospection.

The Laser Doppler Vibrometry (LDV) is an innovative technique that allows the vibration velocity measurement of the elements under test without contact, and that also allows to reach a qualitative and quantitative characterization of superficial layers and building structures. To produce the structure excitation impulse, piezoelectric or mechanics actuators are commonly used. Such technique has already been applied in ND diagnostic monitoring of antique frescoes and, in general, of works of art, as for example wall structures, ancient manufactured items, ceramics and mosaics, [3-8]. Experimental application of LDV on a test wall of 1 m^2 supporting two layers of plaster containing defects artificially realized, has highlighted a different surface vibratory response near the damaged points, [9]. Other results of vibration-based diagnosis both on test panels and on real frescoes and icons can be found in [10]. In this works, the impulse is generated with piezoelectric actuators to transfer the necessary quantity of energy to the structure. LDV often operates in conjunction with acoustic stimulation. An hybrid acoustic-LDV diagnostic technique is compared in [11] with the traditional hammer excitation, and an acoustic stimulation is applied in [12] to a wide number of artificially aged structures with the purpose to locate and to characterize the defects. An interesting scanning instrumentations designed to automatically detect the fresco damages by acoustic excitation and microphone acquisition is reported in [13]. Finally, the preliminary operations to the creation of an acoustic device that associates the signal acquired through a microphone to the signal acquired through LDV is described in [14]. With such method, that shows effectiveness only for not too small fresco separations, a damage is identified by a sensitive indicator to the perturbation of the phase of the FRF around an anti-resonance point.

In this work a ND&NI technique based on acoustic excitation and LDV identification of mechanical vibrations is presented. The measuring methodology is validated on a test panel realized in laboratory, firstly excited by the instrumented hammer. Different delamination thicknesses are taken in consideration, and the adoption of an acoustic absorption coefficient to individuate possible sub-superficial discontinuities is finally discussed.

2. EXPERIMENTAL SET-UP AND TESTS

2.1 Realization of the laboratory panel. A test panel has been realized with the purpose to investigate on the possibility to use LDV for the diagnosis of the health state of antique frescoes, particularly for the survey of detachments, cracks and delaminations. The test panel has been built with the same traditional technique of an antique fresco to emulate its layered structure. The panel, as shown in figure 2, is made of a concrete square tile

0,5x0,5 m wide. To emulate the gap that arises after a separation among the plaster layers or between the plaster and the wall when a detachment in the fresco occurs, a series of interposed materials is laid on the panel during its preparation. In particular, 9 sample disks of different materials have been inlaid with known geometry and location. In order to not bring out of alignment the disks during the panel preparation, a drop of glue is laid between disks and cement. After that, a layer of plaster 8 mm thick has been applied above the cement and the disks. For simplicity, only one layer has been applied.

As shown in figure 2, all the disks have the same shape: they are circular, with diameter of 80 mm and variable thickness between 0,1 mm and 2,5 mm. The center of each disk is placed on a grid, 160 mm one from another and 90 mm from the edge of the panel, to form a regular array. To each row has been assigned a letter (A-B-C), and to each column a number (1-2-3). Such arrangement allows to recognize each disk typology during the data survey, to relate the dynamic answer of the delaminated areas to the respective material and its thickness. The choice of the materials is for something particularly yielding and that doesn't absorb excessive water to not alter the water concentration in the plaster. The materials inlaid in the various positions of the grid, and the relative partial and total thicknesses are listed in table 1.

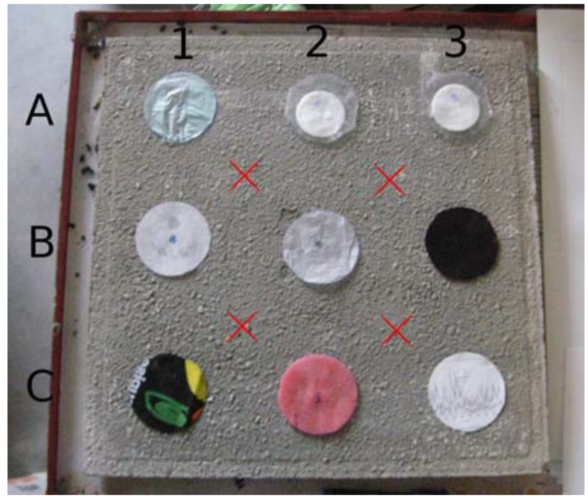

Figure 2. The test panel.

After the glue dried up, the concrete has been dampen up to saturation. This absorbs a lot of water, that quickly enough spreads inside the material. To prepare the plaster on the dry cement means to alter the concentration of water in the inside layers of the same plaster causing a great brittleness and crumbliness of it. The following step has been the choice of the lime mortar. An industrial premixed plaster has been preferred rather than to realize it by mixing sand and lime, both for saving time and for demands of precision of execution and inexpensiveness: the cost of the premixed is more or less equal to the sum of the costs of lime and sand. The chosen mortar doesn't contain cement, this type of mortar has considerably shorter drying times. The plaster has been realized with 5 kg of lime premix and around 1 liter of water, mixed slowly to have a homogeneous mixture. During the application, the superficial state has been worked the most homogeneously possible with trowel and float. A surface too wrinkled and rich of imperfections would be able to alter the reading of the laser spot. To make easier the data reading, the points of measure have been gently smoothed down with sandpaper. No pigments have been applied to the surface because they are not influent on the measurements. The finished panel ready for the measurements is illustrated in figure 3.

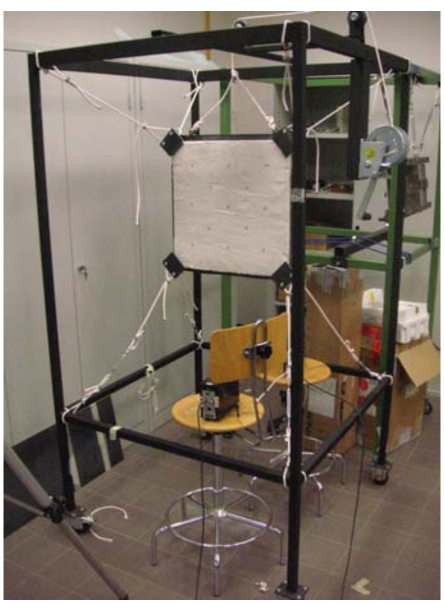
Figure 3. Experimental set-up.

2.2 Base principles and experimental details. To proceed to the experimental tests it has been necessary to build a frame system to carry the structure in a floating way. First, the panel has been installed on a steel frame; a rubber layer has been added between the panel and the framework to damp undesired vibrations and flutters. Such "elastic bed" has subsequently proved non to influence the diagnosis of the detachments, since the vibratory behavior associated to it (below 50 Hz) clearly appears far away the frequencies of interest for the measures. The frame has been therefore fixed to a support structure by means of ropes and connecting rods, as shown in figure 3. The ropes have been made to pass through the 8 vertexes; turnbuckles have been added to the 4 lower ones, to adjust their tightness. The influence of such realized fixing system, i.e. with the panel elastically suspended, on its vibratory behavior is practically negligible.

The impulse on the panel has been transmitted with two different techniques: (i) *impact test*, with an instrumented hamm**er** *Brüel & Kjær* 8202 with a rubber tip and a built-in force transducer; (ii) *acoustic test*, with the two-way loudspeaker Turbosound TXD 121, that consists of a 12” reflex-loaded low frequency driver and a 1” high frequency compression driver with 600 watts program (300 watts r.m.s.), and has a frequency response 60Hz – 20kHz ± 4dB.

The vibration measurement on the panel test points has been realized in both cases with the laser vibrometer Polytec OFV 505 that gives a resolution of 0,05 mms^{-1}/Hz in the range of 10mms^{-1}/V for a distance range from 0,1 to 100 meters.
Measurements have been done aiming the laser ray to the center of each disk, and in 4 points between adjacent disks, equally spaced from the disk centers. These 4 points are indicated in figure 2 with red crosses and in the following identified with Roman numbers from I to IV. These points have been assumed as "healthy": they have been considered sufficiently distant from every disk to disregard their effect. The aim of each test is to acquire the dynamic response in terms of auto power spectrum $G_{XX}(f)$ the velocity signal measured by the Laser Doppler Vibrometer. The auto power spectrum gives information on how the signal power is distributed in the frequencies domain. $G_{xx}(f)$ is gotten multiplying the frequency spectrum $S(f)$ of the temporal signal for his own conjugated complex:

$$G_{xx}(f) = S^*(f)S(f) \tag{1}$$

and may therefore be calculated as square of the module of S in the frequencies domain (f). Comparing the spectral diagrams of “healthy” points with the “defected” ones allows to see which peaks are linked to the structure and which are linked to the defects realized in a known way. The first phase of characterization through impact hammer has the double purpose of validate the investigation technique and to detect the range of frequencies in which to analyze by the acoustic impulse. The resultant diagrams from the acquisition of vibration signals give a FRF (Frequency Response Function) in the frequencies domain ω, that is the relationship between the superficial velocity v of the panel and the impact force F of the hammer. This quantity, defined mobility M, can be considered as the inverse of the mechanical impedance Z:

$$M = \frac{1}{Z(\omega)} = \frac{v(\omega)}{F(\omega)} \qquad (2).$$

With the purpose to reduce the noise and the influence of the low repeatability of the impact strength, in every point has been calculated the average of 4 consecutive measures. Subsequently, the diagram of the coherence of the signal has been plotted.
The tests with acoustic impulse generally offer the possibility to overcome the necessity of physical access to the point of measure (remote investigation). In fact, if a sufficient quantity of energy is transferred by the air to the surface panel and also to the deepest layers, the acoustic wave can induce vibrations in every point on the panel surface. The acoustic waves can be produced in an ample range of frequencies. In particular, the impulse signal that has been used is a burst-random type on a range of frequencies between 700 and 8000 Hz. The exact measure of the force in this case is particularly complex: the calculation of the FRF doesn’t result practical. In order to get a FRF, it would be in fact advisable to measure the impulse signal through a microphone positioned in proximity of the panel surface, near the laser measurement points. In this case, however, the auto power spectrum of the measured velocity signal can be good enough to observe the presence of defects. A first series of measurements has been made to identify the best configuration; two parameters have been considered in this stage of execution: 1. the loudspeaker height referred to the ground; 2. the loudspeaker distance and orientation relatively to the panel. Different combinations of these parameters have been tried.
A second series of acoustic tests has been developed, in order to create an alternative acoustic method for the acquisition of the signal. In this kind of test the signal acquired through LDV, in the same way of the “traditional” test, is associated to the signal acquired through a microphone. In particular, the authors tried to study the possible correlation between the dynamic response of the panel surface in correspondence of a defect and a defined characteristic parameter identifying the surface acoustic absorption. A similar study is reported in [15].
The base principle of this theory is now recalled. The theory considers the power transmitted by an incidental acoustic wave W_i on a material as split in three parts: a fraction W_r is reflected, a fraction W_a is absorbed, and a fraction W_t is transmitted beyond the material itself. Coefficients of reflection, absorption and transmission, are then respectively defined as:

$$R_w = \frac{W_r}{W_i}; A_w = \frac{W_a}{W_i}; T_w = \frac{W_t}{W_i} \qquad (3).$$

The relationship among the coefficients R_w, A_w and T_w can simply be determined by the Law of conservation of energy: $W_i = W_r + W_a + W_t$. From this, it is deduced that: $R_w + A_w + T_w = 1$. A fundamental parameter for the evaluation of the phonoabsorbent performances of a material is the "coefficient of apparent acoustic absorption" α. This parameter is defined as energy fraction not reflected by the material: $\alpha = 1 - R_W$.

The equipment used for this second series of tests consists of a sound card Edirol FA 101 and a microphone Behringer ECM8000 for audio analyzers linear measurement in real time, with a frequency response 15 Hz – 20 kHz. The microphone has been positioned at 4,5 cm from the point under examination while the acoustic box used for the excitation has been set 35 cm behind the microphone. The acoustic box is a home-made speaker system consisting of two coaxial plastic tubes of 120 and 95 mm in diameter and 330 mm in length. This second experimental set-up is showed in figure 4. The laser vibrometer is positioned behind the system in line with the speaker and the microphone. The commercial software Adobe Audition v1.5 has been used for the contemporary stereo recording of the signals. It is a professional software for the multi-track audio recording on hard disk. The analysis of the data and the creation of the signals reproduced by the loudspeaker have been performed with the Aurora plug-in.

Figure 4. Experimental set-up of the LDV&microphone test.

The frequency response is here calculated from two signals: the input is the pressure transmitted to the system through the loudspeaker and measured by the microphone; the output is the vibration velocity as measured by the LDV. As excitation impulse signal a logarithmic-sweep on a range of frequencies between 200 Hz and 15 kHz has been chosen. Since the signal is distorted and contaminated by noise, a de-convolution, that is an algorithm-based process used to reverse the effects of convolution on recorded data, is therefore necessary to obtain the system response. Usually many impulse responses are obtained, but only the last one is the response to the linear impulse, the previous ones being the products of harmonic distortion. The responses to the linear impulse of the laser and the microphone respectively correspond to the velocity variation of the panel and the pressure variation near the point under examination. Holding eq. (3), the coefficient of absorption can be obtained.

3. RESULTS AND DISCUSSION

3.1 Impact test. Some results of the dynamic tests on the test panel are summarized in the graphs of figure 5, that shows the FRF of points from A1 to C3 in comparison with not-defected points. It can be noticed that in a range between 2500 and 3500 Hz the defected points show very high peaks not found over the healthy areas. Outside of this range, many peaks in the FRF appear; these have not been considered because they are found both in the FRF of the defected and not-defected points, and certainly correspond to resonance frequencies of the structure. At low frequencies, under 30 Hz, the measurement points show a different behavior. It has been noticed that the peaks below 30 Hz strongly depend on the panel hanging conditions, because aiming the laser in the same point and tightening or loosening the connecting turnbuckles that bind the frame, extremely different dynamic response around this frequency are obtained. Because of this, the zone under 50 Hz has not been investigated. Besides, in the range between 2500 and 3500 Hz the coherence of the defected points is far higher than for the healthy ones.

3.2 Acoustic test. With regard to the results of the acoustic tests, in all tested configurations the peaks of the auto power spectrum of the delaminated areas can be clearly distinguished in the range between 2500 and 3500 Hz. A good match with those already noticed in the hammer tests is found, as figure 6 illustrates.
Another similar range shows up, around 5500 – 5600 Hz. During the acoustic tests it has been noticed that more than the distance or the height of the loudspeaker, the factor that mostly influences the quality of the signal is the relative orientation of the loudspeaker with respect to the panel. The test in which the speaker is turned to 270° has given the signal of inferior quality, while when the acoustic wave is turned toward the wall (as in the cases 90° and 180°) the signal is somehow reflected and the graphs result cleaner, being greater the ratio signal/noise. When the speaker is turned 270° it is in fact turned toward the open space of the laboratory and the signal doesn't get reflected, scatters and gets dirty.
With regard to the signal coherence, it is next to 1 in the whole characteristic range of the defect when the orientation is 0° (situation in which it prevails the direct wave), and progressively goes dirtying with the increase of the loudspeaker-panel relative angle. In conclusion, the selected configuration is the one with the speakers directly facing to the panel (orientation 0°), lying 120 cm from it and raised 55 cm on the ground.

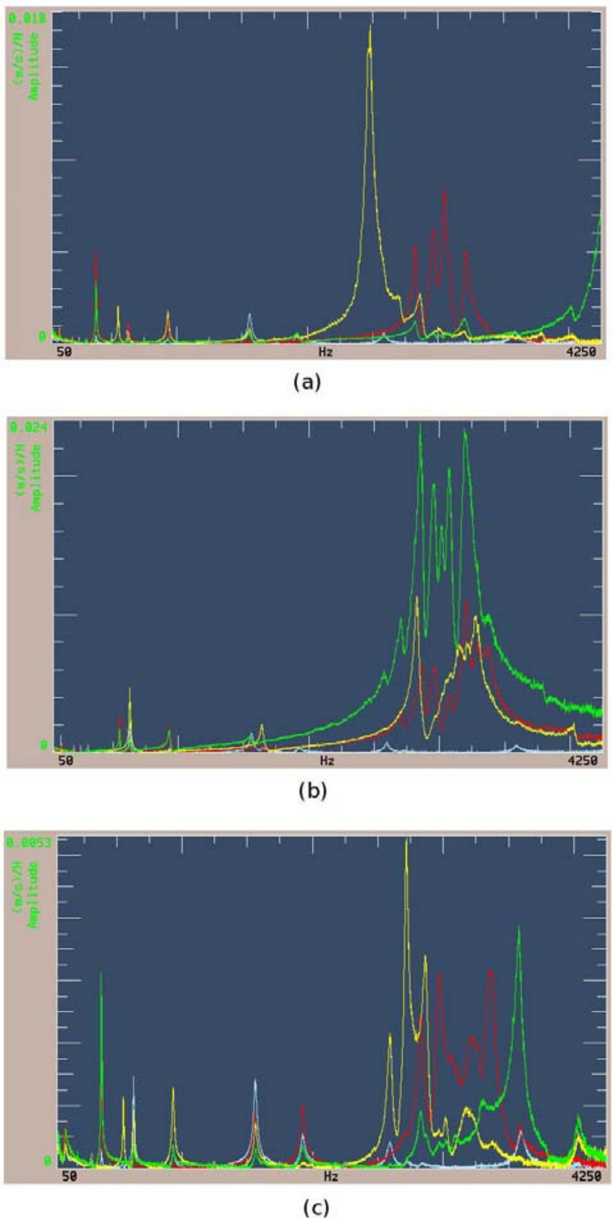

Figure 5. FRF functions of impact test: (a) delaminated points (d.p.) A1 (green line), A2 (yellow line), A3 (red line) and healthy point (h.p.) II (gray line); (b) d.p. B1 (green line), B2 (yellow line), B3 (red line) and h.p. I (gray line); (c) d.p. C1 (green line), C2 (yellow line), C3 (red line) and h.p. IV (gray line).

In comparison with the FRF obtained with the impact test, a frequency range is still found, in which the auto power spectrum value increases considerably in presence of delaminated layers, of one or two orders of magnitude if compared with not defected zones. Such range corresponds to the characteristic one of the damaged points previously detected by means of impact test. In correspondence of the healthy points the mobility is lower than in the defected ones, being present only some peaks associated at the resonance of the structure as previously underlined. This can clearly be seen also looking at the power auto-spectrum produced by acoustic excitation, that assumes extremely low values between 2500 and 3500Hz. None of the 4 healthy points produce peaks of meaningful value.

If a possible correlation among mobility in the various lacked points and thickness of the correspondent disk is investigated, it can be noticed that there is not a direct correlation among thickness of the material used for reproducing the void and mobility in the dynamic response. In other words, the thickness of a sub-superficial void in a fresco does not seem to influence the vibrational behavior of the superficial layer laying over it.

The trend of the coefficient of apparent α is depicted in figure 7. It presents some characteristics peaks at frequencies in the range where the auto power spectrum is higher: between 2500 and 4000 Hz and between 8000 and 12000 Hz the defected points show higher α values. This behavior is absent in not-defected points. These tests show values of the coherence close to 1 in correspondence of frequencies where $\alpha = 1$: it indicates a totally absorbent surface.

4. CONCLUSIVE REMARKS

The laboratory activity presented in this paper focuses on the applicability of a completely not-invasive not-destructive technique for the diagnosis and the health monitoring of antique frescoes. Measurements have been conducted on a test panel built following the traditional technique of a fresco, and in which some defects have been artificially introduced. The measurement technique is based on a traditional modal analysis system with impact hammer and on an acoustic system for structural excitation. An optic laser system is used for the measure of the superficial vibrations of the fresco. The analyses, even though at a preliminary state of the experimentation, have been able to conduct to some meaningful observations. The tests with the impact hammer have shown that there are substantial differences in the surface vibrations between healthy points and points corresponding to detachments or sub-superficial separations: the surface mobility demonstrate to be a valid index of the presence of a separation between support and plaster. The shape of the FRF of defected points strongly depends on the material used to create the void. Factors that influence the shape of the FRF could be the mass, the density, the elastic constant and the damping factor of the material. The maximum value of the mobility however is not directly proportional to the thickness of the defect.

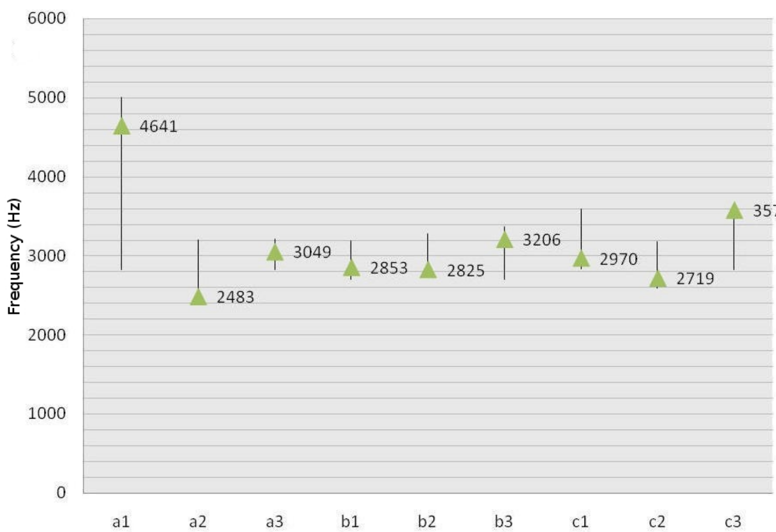

Figure 6. Frequency auto-spectrum range of delaminated points obtained by acoustic test (black segments) and maximum mobility frequency of FRF obtained by impact tests (green triangles).

The results of the acoustic tests confirm the presence of some peaks characteristic of the defects, also found with the impact hammer. In both cases, in a range between 2500 and 3500 Hz, the function of reference (FRF or auto power spectrum) assumes extremely high values if a defect is present under the external surface of the panel while it shows low values and doesn't introduce significant peaks for the healthy points.
On the other hand, using a system of acoustic excitation it is not possible to determine, if not in an approximate way, the value of the input force. Because of this, the realization and the reading of the FRF graphs result particularly difficult. Nevertheless, these tests show that the analysis of the auto power spectrum of the signal in velocity is sufficient to detect the range in which the characteristic peaks of the defects are found. By comparison with results from ref. [9-13], it is noticed that when the test is realized on a true wall the FRF function grows of one or two orders of magnitude on a range of frequencies between 2 and 4kHz only if the defect is present. The coherence diagrams are similar to those obtained in this work; also in this case the form of the functions strongly depends on the defect morphology.
The present study showed that substantial differences among defected and not defected points in the fresco can be noticed also from the analysis of the coefficient of apparent acoustic absorption. In the ranges between 2500 and 4000 Hz and between 8000 and 12000 Hz the function assumes high values if a defect is present and low values for healthy points. Also the coherence graphs introduce values next to 1 in presence of defected zones. The graphs of the coefficients of absorption of the defected points strongly depend on the material used for simulating the void, but the maximum values are not directly proportional to the thickness.
In conclusion, on the authors' opinion the applicability of this methodology in the diagnosis of antique frescoes is evident: the analysis of the coefficients of absorption for the identification of possible detachments between the state of plaster and the wall is effective. A great limitation is that this method doesn't give valid information for the knowledge of the extension and depth of the detached zones. It must be highlighted in fact that in these tests the position and the dimensions of the defects were known *a priori*; in this case it has been simple, by comparison between output data, to recognize some dynamic response as that of defected points. This must be absolutely considered when the methodology is applied to a real case: to have meaningful data on a structure with unknown dynamic behavior, it is necessary to analyze numerous points and to effect comparisons among them.
However, the research is not concluded. The applicability of this diagnosis technique to real frescoes has to be experimented. The greatest efforts will turn to the development of the acoustic technique through the refinement of the measurement instrumentation characterized by the total lack of contact with the work of art.

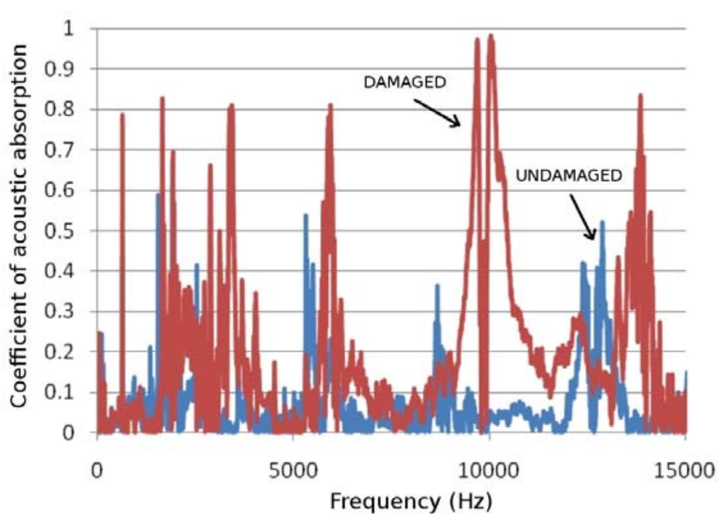

Figure 7. Coefficient of apparent acoustic absorption of healthy point II (blue line) and delaminated point B2 (red line).

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