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NON-DESTRUCTIVE DIAGNOSTICS OF TIMBER ALTARPIECES: SOUND-INDUCED LASER VIBROMETRY FOR EARLY DETECTION OF DELAMINATION

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Abstract

The preservation of cultural heritage requires non-destructive techniques to assess the condition of historical artifacts. This study examines the dynamic behavior of a timber altarpiece replica, covered with traditional plaster and painted layers, using laser vibrometer technology. The goal is to analyze its response to low-volume sound levels and to detect early signs of delamination by identifying increased vibration amplitudes in compromised areas.
This approach effectively detects vibration patterns that indicate potential delamination before visible damage occurs, highlighting the value of laser-based techniques for non-destructive diagnostics and the preservation of cultural heritage.

Keywords: Cultural heritage preservation, Non-destructive testing, Laser vibrometry, Dynamic response analysis, Structural health monitoring, Delamination detection.

1 INTRODUCTION

Vibration stresses can significantly impact artworks, leading to various forms of damage such as cracking in paint layers, detachment from the substrate and general material loss [1].
In the measurement of vibrations, it is common to use devices securely attached to the object being examined [2, 3]. While this approach is applicable to most structures, it is generally not suitable for the surfaces of artworks, as they should be handled as minimally as possible. For this reason, in previous research, the authors tested a non-invasive acoustic method to analyze the dynamic behavior of a replica of the *San Giobbe altarpiece*'s structure, a Renaissance wooden panel painting by Giovanni Bellini, using laser vibrometry [4]. The results demonstrated that acoustic laser vibrometry effectively identified resonance frequencies, confirming its potential for non-destructive diagnostics in cultural heritage study and preservation.
Building on this work, the present study extends the analysis by incorporating additional non-structural layers of gesso and paint, enabling the early detection of damage through experimental investigations. A common form of damage in such artworks is delamination, which refers to the partial and localized loss of cohesion between adjacent layers of paint or between the paint and the underlying substrate [5, 6]. Early detection of detachment is important to prevent further deterioration and enable timely restoration [7, 8, 9].
This article presents the analyses conducted, the data obtained and relevant considerations arising from the study.

2 CONSTRUCTION OF THE ALTARPIECE REPLICA

The *San Giobbe altarpiece* (Fig.1) was painted by the renowned Italian artist Bellini between 1477 and 1478. Originally, the artwork adorned the second altar in the church of *San Giobbe and San Bernardino* in Venice (Italy), but it was transferred to the *Gallerie dell'Accademia* in 1815 for conservation purposes.
The 453×259 cm panel consists of 13 poplar boards reinforced by four larch beams and trapezoidal wooden wedges for structural stability [10].



Fig. 1 – San Giobbe Altarpiece (Courtesy of the Gallerie dell'Accademia, Venice, Italy).

To conduct the tests in a controlled environment, at the *Giorgio Macchi* laboratory of DICAr, University of Pavia, a replica was constructed to study the original artwork and similar altarpieces, focusing on both structural and non-structural layers. The wooden base, previously tested [4], consisted of two poplar boards, four larch beams and 32 fir wedges, all assembled with bone glue.
Building on the completed wooden structure, the next phase of the project focused on the addition of non-structural layers to reflect the original techniques used in the creation of the artwork (Fig. 2).



Fig. 2 – San Giobbe Altarpiece Replica Specimen.

The surface preparation began with sanding the wood for better adhesion. A protective layer of gesso and rabbit skin glue was applied in multiple layers, reaching a final thickness of 3 mm after drying and sanding (Fig. 3a).
Unlike some paintings from the same period, photographic analysis suggests the original artwork lacked a canvas layer, though part of the replica was prepared with loosely woven linen for comparison with other altarpieces from the same time (Fig. 3b).
Finally, the gesso and glue mixture were applied over it to complete the preparation (Fig. 3c).



Fig. 3a – Preparation of the protective layer; Fig. 3b – Addition of a loosely woven linen canvas; Fig. 3c – Finalized protective layer.

The painting process reproduced both oil and tempera techniques, reflecting findings from the original [11, 12]. The oil paint was prepared with a linseed oil-pigment mix (1:3 ratio), ground to a smooth paste, forming a 0.2-mm-thick layer (Fig. 4a) [13]. The tempera layer used egg yolk as a binder, with pigments mixed into an egg-water solution, forming a 0.3-mm-thick layer (Fig. 4b) [14].



Fig. 4a – Preparation of oil paint; Fig. 4b – Preparation of tempera paint.

2.1 Simulated Damage

The tests aimed to develop non-invasive diagnostics for early defect detection. For this reason, two types of simulated damage were created on the wooden substrate before applying the protective layer to replicate degradation in historical panel paintings: micro-fractures mimicking worm/termite attacks and localized visually imperceptible paint lifting, and larger defects such as delamination and partial detachments, simulating advanced deterioration.
Fig. 5 schematizes the damage simulated on the specimen and the significant points selected to test the greatest number of possible combinations between painting technique, presence or absence of canvas and type of damage. Table 1 identifies the characteristics of the points that will be analyzed in the following paragraphs (Tab. 1).

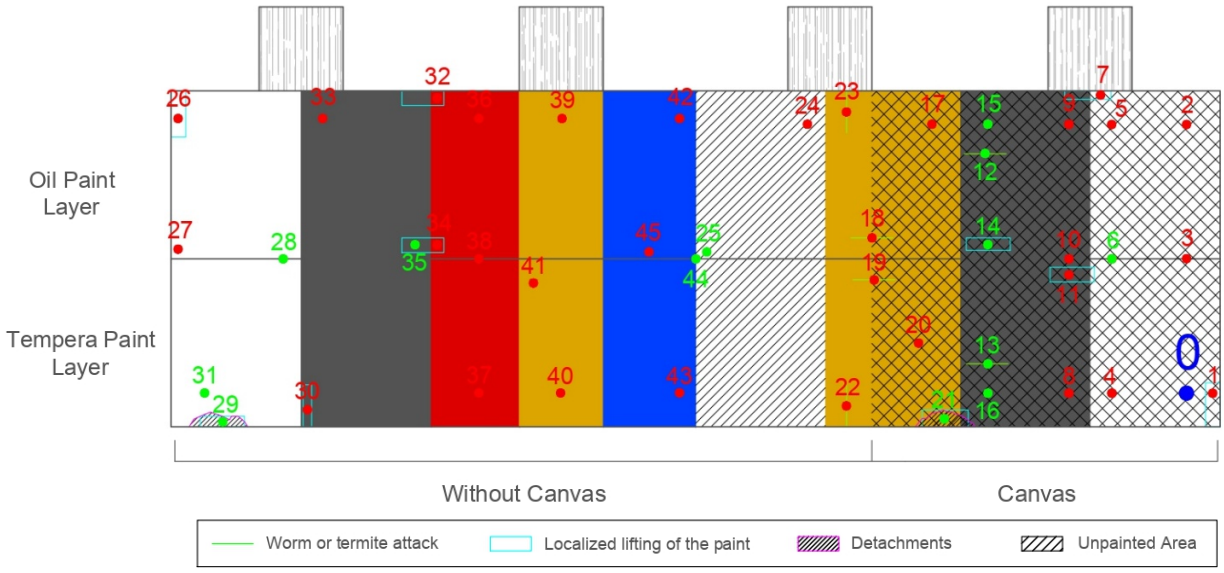


Fig. 5 – Monitored points.

Point Number	Color	Painting Technique	Presence of Canvas	Simulated Damage
1	White	Tempera	✓	Paint Bulge
6	White	Tempera/Oil	✓	Junction
12	Black	Oil	✓	Cut
13	Black	Tempera	✓	Cut
14	Black	Oil	✓	Paint Bulge
15	Black	Oil	✓	Intact
16	Black	Tempera	✓	Intact
21	Brown	Tempera	✓	Detachment
25	Gesso	Gesso	✗	Intact
28	White	Tempera/Oil	✗	Junction
29	White	Tempera	✗	Detachment
31	White	Tempera	✗	Intact
35	Black	Oil	✗	Paint Bulge
44	Gesso	Gesso/Temp/Oil	✗	Junction

Table 1: Properties of the measurement points.

2.1.1 Worm or termite attack

Woodboring beetles are insects that tunnel through wood, damaging its structure and threatening the stability and artistic value of wooden artworks. Signs of infestation include small holes, fine sawdust or the insects themselves [15]. To simulate this condition, 2-mm-deep cuts were made in the wood before adding the protective layer to mimic the damage caused by worms or termites (Fig. 6).



Fig. 6 – Simulation of worm or termite attack.

2.1.2 Localized lifting of the paint

Loss of adhesion between the support and the upper layers can weaken the preparatory layer, leading to localized lifting on the artwork, which compromises the painted surface's stability [16]. In this study, paint bulges were artificially created by introducing air pockets beneath the paint, simulating early-stage adhesion failure (Fig. 7). If untreated, this can lead to more extensive paint loss over time.



Fig. 7 – Simulation of localized lifting of the paint.

2.1.3 Detachment

The loss of paint layers can occur when the contraction of the support originates stresses in the paint film [17], often due to natural aging [18] or environmental factors [19] such as temperature and humidity [20], or improper conservation conditions, including the absence of protective layers and unsuitable treatments [21]. In some parts of the replica, paint bulges have caused complete detachment, particularly at the lower edges of the altarpiece, leading to the paint separating entirely from the underlying layers (Fig. 8).



Fig. 8 – Simulation of detachment.

3 LASER VIBROMETRIC TESTING METHODOLOGY

A non-invasive approach useful for the objective and reliable assessment of the dynamic behavior of various structural elements (particularly panels, plates and walls [22, 23]) is the acoustic-vibrometric technique. In this method, an acoustic wave with a variable frequency, typically between a few tens and a few thousands Hz, is directed towards the area under investigation. Simultaneously, a highly sensitive interferometric laser vibrometer measures the local oscillations induced by the sound pressure on the structure.

To conduct this investigation, vibrations were induced in the sample using a GEMINI ES-08P MKII active two-way speaker, while the response was measured using two separate laser vibrometers. A Julight vibrometer VSM-1000 (SN: JVSM1000-23-2100) was used to monitor a fixed reference point (Point 0), which remained constant throughout the test to serve as a baseline. Meanwhile, a vibrometer (SN: JVSM1000-21-1085) was used to scan different locations

across the altarpiece, allowing for a comprehensive mapping of its vibrational behavior. The signal generation and data acquisition were managed through a National Instrument NI-USB 6212 multifunction DAQ board, ensuring precise synchronization of all measurements. This experimental setup enabled a detailed investigation of the structural response of the object, highlighting variations in stiffness, the presence of paint detachment and other mechanical characteristics.

The signal analysis was carried out using the Frequency Response Function (FRF) approach, which represents the ratio between the vibrations measured at a specific point and those at a reference location, allowing spectral analysis to characterize the specimen's frequency response. To this end, frequency spectra were derived from the vibrometer's output signal. The experimental setup is shown in Fig. 9.



Fig. 9 – Completed experimental setup for the acoustic-vibrometric analysis.

To carry out this type of analysis and identify any defects, the altarpiece was constrained at the upper edges and subjected to a defined sound sweep, where the sound frequency gradually varied from 10 Hz to 1500 Hz over 10 seconds (human speech typically ranges between 250 and 350 Hz), allowing for the excitation of all frequencies (Fig. 10). By gradually sweeping through the range of frequencies, the method enables the detection of specific vibrational responses linked to structural anomalies, such as delamination or other forms of damage.

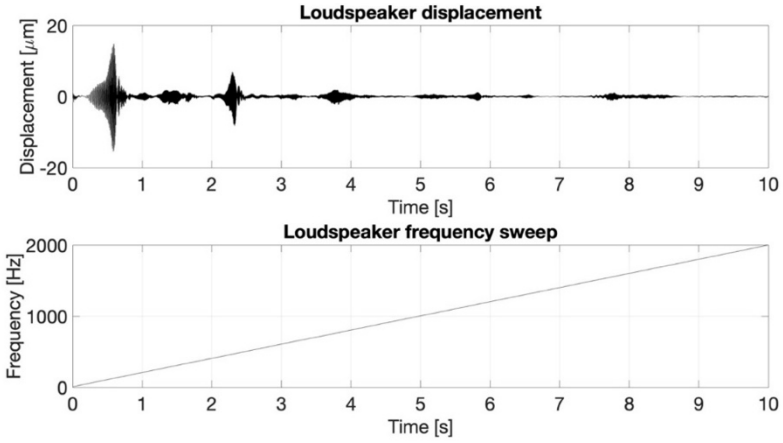


Fig. 10 – Loudspeaker sweep.

Once the setup was completed, the analyses were performed by identifying significant points selected to test the greatest number of possible combinations between painting technique, presence or absence of canvas and type of damage (Fig. 5). Table 1 identifies the characteristics of the points that will be analyzed in the following paragraph (Tab. 1).
A reference point (Point 0) was set at 80 mm from the lower edge and 80 mm from the right lateral edge, positioned on the canvas. This reference point remained constant throughout the test, while the laser was moved across specific locations to map the different tested conditions. The replica was divided into eight color bands to assess the laser's ability to read different shades. The results showed that the black areas were difficult for the laser to read due to their low reflectivity, while white bands had excellent readability. To facilitate potential future tests on an untreated surface, a section between the blue and brown areas was deliberately left unpainted, exposing only the underlying gesso and glue layer.

4 EXPERIMENTAL RESULTS

The laser vibrometric tests conducted on the acoustically-excited replica of the *San Giobbe altarpiece* revealed distinct differences in the local dynamic behavior of the structure, influenced by the presence of damage, its material composition and structural conditions. In the following sections, the FRF analysis will focus on investigating how damage manifests in different conditions and how the laser vibrometer can effectively detect it in each case.
The Frequency Response Function (FRF) represents the ratio between the vibrations measured at a specific point and a reference point (point 0). It is calculated by applying the Fourier Transform (FFT) to both signals, converting time-domain data into the frequency domain. This process filters out ambient noise and highlights the frequencies relevant for modal analysis. In the following graphs, the FRF is shown in terms of frequency and gain, where gain represents the displacement ratio between the measured point and the reference point.
Note that the x-axis of the graphs has been cropped at 600 Hz, as no appreciable differences or relevant information were observed at higher frequencies.

4.1 Influence of Simulated Damage on Vibrational Response

An important observation concerns the regions where damage is either forming or already present. This section examines how different types of damage (such as paint bulges, detachment and woodworm holes) affect the vibrational response, providing a detailed analysis of their impact through the following subsections.

4.1.1 Vibrational Response of Paint Bulge area

The FRF graph recorded at Point 1 (Fig. 12), located on a paint bulge, highlights how the delaminated paint vibrates independently from the substrate. At low frequencies (<100 Hz), the response shows low gain, while above this threshold vibrations become more pronounced with distinct peaks. The first resonance peak appears at 150 Hz, aligning with theoretical calculations for a simply supported beam (an idealized model for the bulge) with dimensions of approximately 100 mm × 35 mm × 0.3 mm, an elastic modulus for tempera of 3×10^9 Pa [24] and a density of 1200 kg/m³. The expected natural frequency of approximately 125 Hz confirms the test results and supports the beam-like behavior of the bulge.
This is particularly important as it enables the non-contact identification of areas where damage is beginning to form, allowing for timely restoration interventions before full detachment occurs.

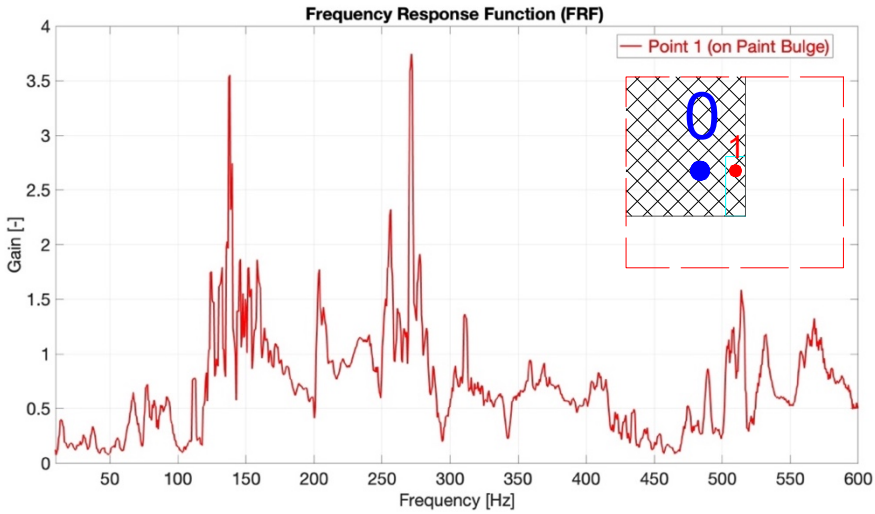


Fig. 12 – Point 1 (on a paint bulge).

4.1.2 Vibrational Response of Detachment

Regions where full delamination has occurred exhibit high vibration amplitudes, as the detached layers resonate freely due to their weaker structural connection to the underlying substrate. This effect is particularly evident when comparing points 29 and 31 (Fig. 13). Point 29 (red), positioned on a delaminated area of tempera, shows a significant peak at low frequencies (approximately at 35 Hz), which aligns with expectations. The delamination can be modeled as a cantilever beam [25] and a analytical calculation using the same dimensions and material properties as the paint bulge yields a natural frequency of approximately 30 Hz, closely matching the test results. At this frequency, the amplification reaches a value approximately five times higher than point 31 (green) in the intact region, which exhibits a much lower amplitude at the same frequency.

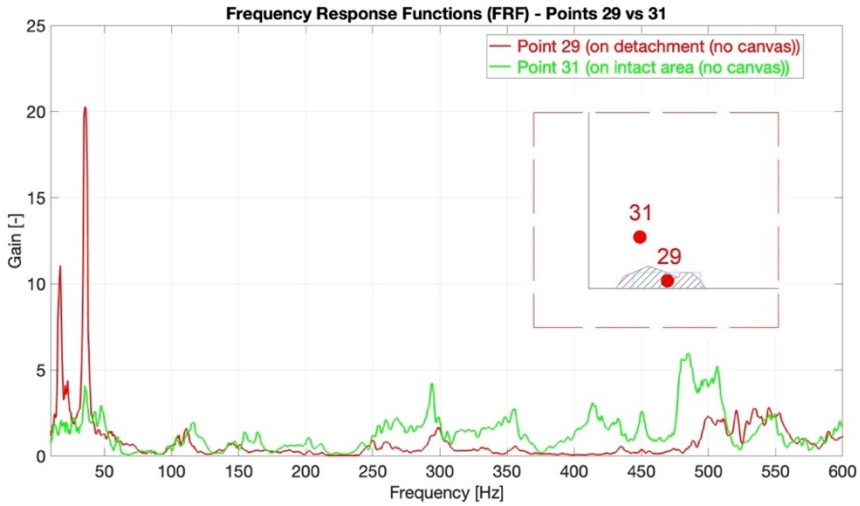


Fig. 13 – Comparison between point 29 (on detachment) and point 31 (on intact area).

As in the previous case, the overall trend remains the same where the canvas is present (Fig. 14): the delaminated area (Point 21, in red) still exhibits higher and more pronounced peaks at lower frequencies compared to the intact area (Point 16, in green). However, the presence of the canvas adds stiffness to the structure, resulting in generally lower amplitude values than in the case with only the wooden support, gesso and paint.

Additionally, a peak at around 500 Hz is observed here, as well as in the following graphs. The reason for this peak is unclear and should be further investigated.

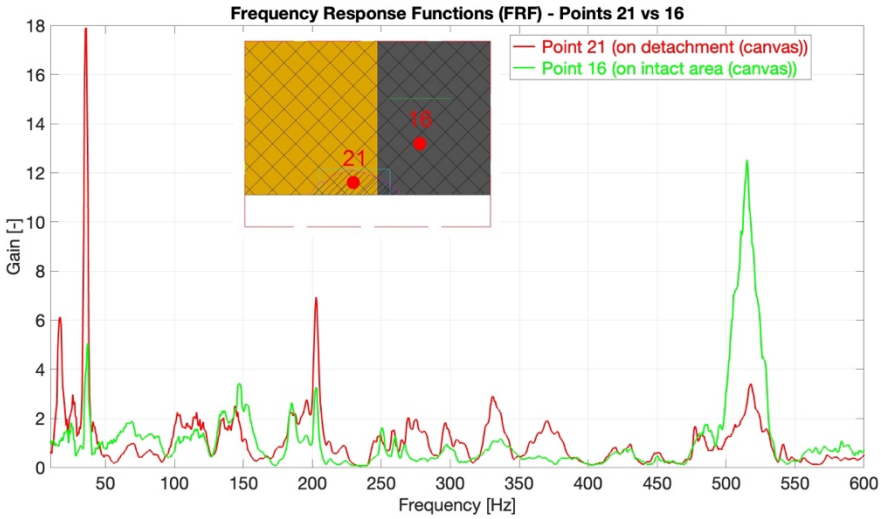


Fig. 14 – Comparison between point 21 (on detachment) and point 16 (on intact area).

4.1.3 Vibrational Response of Cuts

No significant differences were observed between intact areas and the ones where cuts were made to simulate woodworm damage. This was evident when comparing points 12 and 15 on the oil painting (Fig. 15), as well as points on the tempera painting. The lack of a clear distinction suggests that the paint layers contribute to the transmission of vibrational energy across the simulated cuts, allowing the material to behave as if it were intact. Further refinements in damage simulation methods, as deeper cuts, could help clarify these effects in future studies.

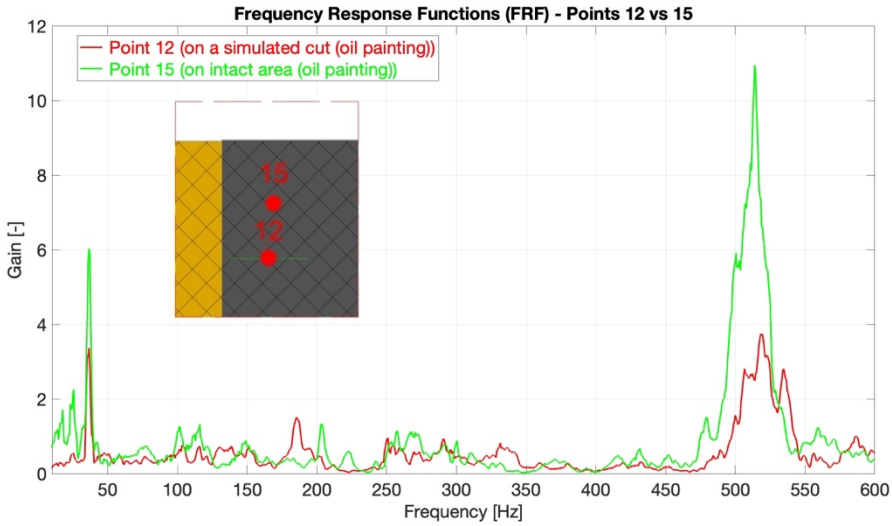


Fig. 15 – Comparison between point 12 (on a simulated cut) and point 15 (on intact area) in the oil painting section.

However, the junction between the two panels can be considered as a discontinuity, similar to the cracks that naturally form in wood over time as it ages and undergoes stress. For this reason, the difference between a point on the panel (25, green) and a point directly on the junction (44, red) has been analyzed (Fig. 16). At low frequencies (around 35 Hz), point 44 shows

significantly higher amplitudes, indicating reduced stiffness at the junction and highlight it as a mechanically weaker zone. Between 100 and 400 Hz, both points exhibit similar trends, though the junction transmits more vibrations.

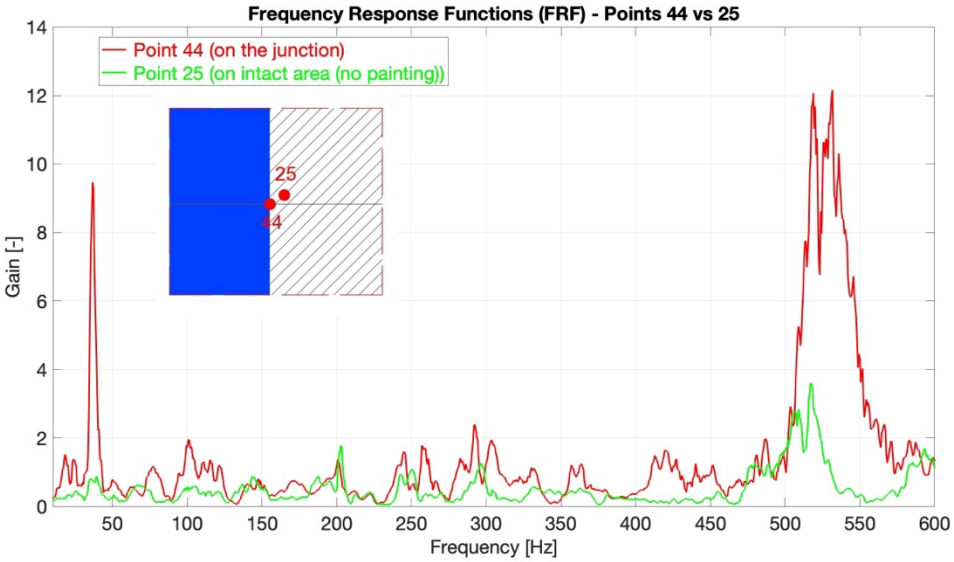


Fig. 16 – Comparison between point 44 (on the junction) and point 25 (on intact area).

4.2 Influence of Canvas on Vibrational Response

The analysis of FRFs highlights how the presence of a canvas layer alters the vibrational behavior of a wooden structure and influences damage detection. The canvas increases the stiffness of the system, acting as a constraint which results in a more uniform response. In contrast, areas without canvas experience more pronounced difference in vibrations' amplification between an intact area and a damaged one due to the direct interaction between the paint layers and the wooden support.

Figures 17 and 18 compare correspondent pairs of points with mirrored positions on the sample: points 14 and 6, both located on canvas, and points 35 and 28, both outside the canvas. In each pair, one point lies on a paint bulge (points 14 and 35), while the other is positioned on a junction (points 6 and 28).

In the first case, shown in Fig. 17 (on canvas), the FRF curves of points 14 and 6 follow a similar trend, with limited differences in amplification. This suggests that the canvas layer contributes to the homogenization of the dynamic response, making it harder to detect localized anomalies such as paint bulges due to its increased stiffness.

In contrast, Fig. 18 (off canvas) shows a much more pronounced difference in the dynamic behavior between point 35 (on a paint bulge) and point 28 (on a junction), which become particularly evident above 250 Hz. Without the canvas, local variations in stiffness produce clearer amplification effects in the FRF, making such discontinuities more evident.

This comparison indicates that, while the canvas contributes to long-term preservation by damping overall vibrations and minimizing structural resonances, it also constrains the dynamic response, potentially hiding early signs of detachment or weakness.

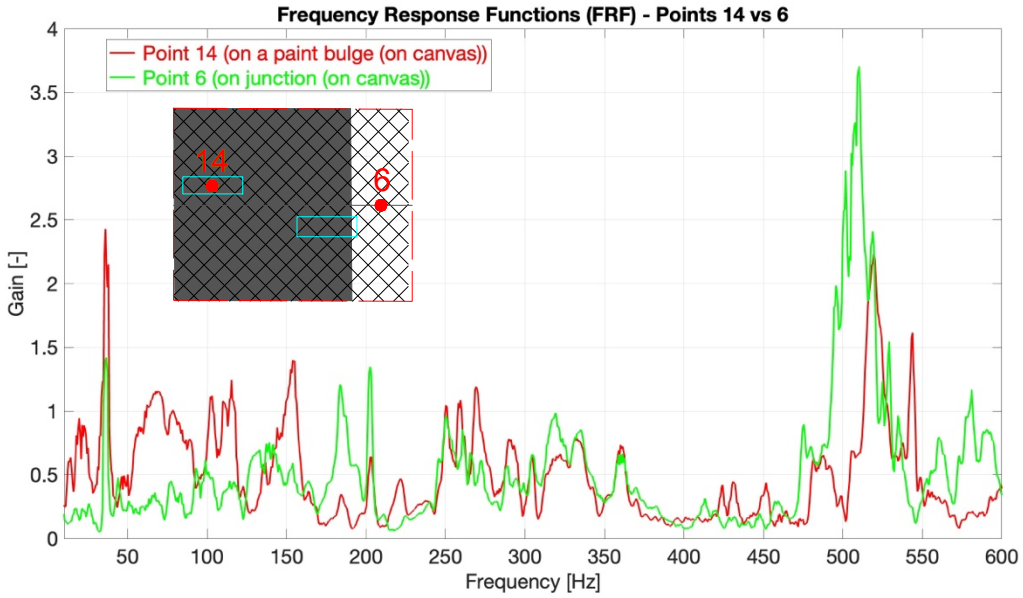


Fig. 17 - Comparison between point 14 (on a paint bulge) and point 6 (on the junction) both on canvas.

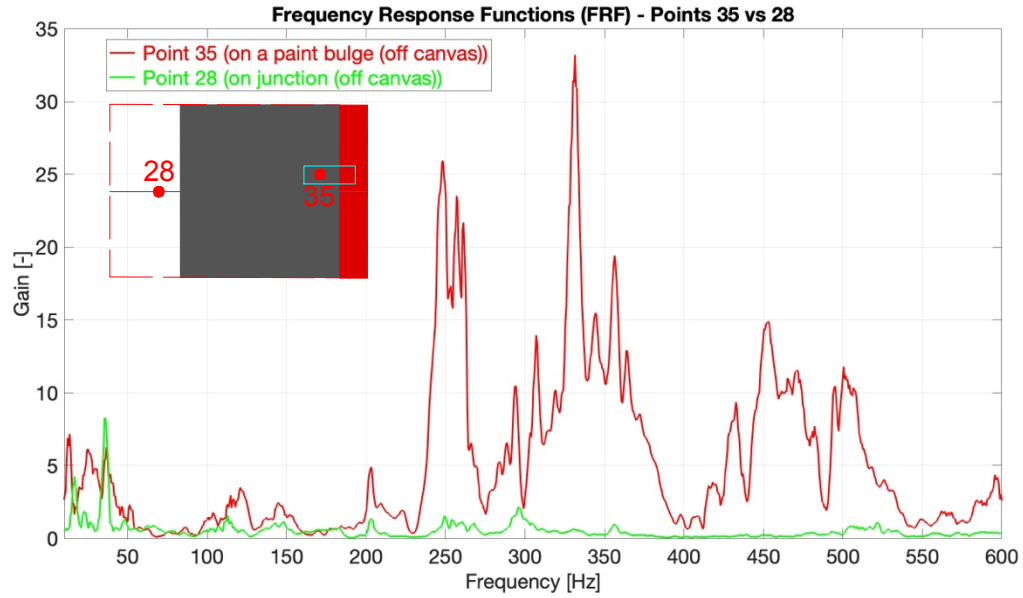


Fig. 18 - Comparison between point 35 (on a paint bulge) and point 28 (on the junction) both off canvas.

4.3 Influence of Painting Technique on Vibrational Response

The comparison between the oil painting technique and the tempera technique did not reveal any recurring pattern that would suggest a significant difference in their vibrational behavior, likely because their stiffness is comparable. However, this is not particularly relevant, as the purpose of the laser in a real setting is not to determine the painting technique used, but rather to identify the onset of damage in a preventive manner. This was confirmed by the analyses of an intact point and a paint bulge in the oil painting, as well as an intact point and a damaged area in the tempera painting.

The findings suggest that laser vibrometry can effectively detect anomalies in both oil and tempera paintings, despite differences in how the damage manifests. The response varies depending

on whether the anomaly is a fully detached area or a constrained deformation, but in both cases, the technique proves capable of identifying early signs of damage.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

The laser vibrometric tests conducted on the acoustically excited replica of the *San Giobbe altarpiece* demonstrated the effectiveness of this non-contact technique in detecting structural anomalies and damage. The analysis of the Frequency Response Functions (FRF) provided insights into how delamination, material composition and structural constraints influence the vibrational response of the painting.

The results show that regions with paint bulges and delaminated areas exhibited higher vibration amplitudes which is consistent with the theoretical modeling of delamination, making them easily distinguishable from intact regions. The paint bulges, being early-stage detachment, demonstrated a marked resonance peak around 150 Hz, supporting the beam-like behavior of the bulge. Detecting these anomalies allows for preventive conservation measures before full detachment occurs. The presence of full delamination further amplified the vibrational response, particularly at 35 Hz, as detached layers resonated independently due to their reduced stiffness. This behavior, observed consistently across both the tempera and oil painting sections, confirms that both paint bulges and full delamination can be effectively detected through laser vibrometry, thanks to their pronounced amplification peaks. In contrast, simulated woodworm damage did not produce a measurable difference in vibrational response, likely due to the paint layers bridging the gaps and maintaining overall stiffness. This suggests that further refinements in the simulation of such damage, as deeper cuts, may be necessary to better understand its impact on vibration behavior.

The presence of the canvas was found to play an important role in altering the vibrational response. While it increases structural stiffness that may help mitigating long-term degradation, it also limits the dynamic response, making damage detection more challenging compared to vibrations in non-canvas areas which have generally more pronounced amplifications. This highlights a possible limitation of the technique when applied to artworks with extensive canvas layers.

Finally, while the comparison between oil and tempera painting techniques did not reveal a distinct trend in vibrational behavior, the laser vibrometry method effectively detected structural anomalies in both cases. The differences observed were primarily due to the nature of the damage rather than the painting technique itself.

Overall, these findings confirm that laser vibrometry is a highly sensitive technique for detecting delamination and other structural anomalies in panel paintings, enabling early intervention before more severe damage occurs.

The next steps of the research will first involve conducting the same tests on an actual altarpiece within a real museum setting. The results obtained so far have demonstrated that the applied sound volume at the tested frequencies did not cause damage to the altarpiece's replica. This confirms the feasibility of performing these tests on a real artwork, allowing for a direct assessment of the technique's applicability in a conservation environment.

Beyond this, future research will analyze shaker tests of tempera specimens to determine the material's failure under fatigue cycles and controlled vibrations, aiming at defining its Wöhler curve (stress vs. number of cycles) [26].

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