Chapter 4
Safeguarding Masterpieces: Multi-point Vibrometry (MPV) Based Monitoring of Georgia O'Keeffe's Art

David Damiani, Dale Kronkright, and Vikrant Palan

Abstract The process of understanding the state of preservation of any work of art is complex. Like most individually fabricated objects, artworks are inevitably anisotropic structures, consisting of amended materials, often irregularly applied, each with slightly different aging characteristics, and each with individual histories of use, environmental exposure, travel, and repair. Much of the responsibility of preserving these works for future generations falls to museum conservators, who utilize a range of analytical and imaging techniques to understand the materials and techniques employed by the artist and to characterize the effects of time, environmental exposure, damage, and cumulative fatigue.

Laser Doppler vibrometry can be used by conservators to observe and document the responses of works of art to vibration excitations. In this case study, we introduce the concept of multi-point vibrometry (MPV) for making a full-field vibrational assessment of a Georgia O'Keeffe painting. Georgia O'Keeffe (Sun Prairie, Wisconsin,1887 – Santa Fe, New Mexico,1986), an American artist, created well over two thousand works of art, including oil and pastel paintings, charcoal and graphite drawings, watercolors, photographs and sculptures during her 60-year, professional career. A multi-point vibrometer is composed of multiple single-point vibrometers where the total number and system configuration is customized based on the needs of the test. A MPV system is preferred for applications where the excitations cannot be either continuous or recurring. A few examples of where this approach works well are one-of-a-kind specimens (paintings, space structures), non-stationary excitation or response (wind-tunnel testing, engine run ups, shock) events and cases with time-variant vibration characteristics.

MPV offers great promise for conservators because it allows for the measurement across entire surfaces with a single, low-energy impact. In this paper, we present the framework for a multi-point vibrometer including its construction, components, and a step-by-step process for acquiring data. The proposed approach is sensor agnostic and covers a frequency and amplitude range of 24 MHz and 2 meters respectively. The goal of the study is to demonstrate the use of vibrometry, especially MPV for preemptive maintenance efforts in works of art which in turn will extend its lifetime for generations to come.

Keywords MPV · Full field vibrometry · Impact testing

Background On Paintings Tested

This case study focuses on the vibrational behavior of three canvas paintings by the American modern artist Georgia O'Keeffe in the collection of the Museum of Fine Arts Boston. Like most canvas paintings, the three paintings have gross structural characteristics conceptually similar to a drumhead. A woven, linen canvas was stretched over a rectangular wooden framework, commonly known as a stretcher. The artist then brushed on pigmented oil paints to form the design surface. In some ways, the vibrational response of canvas paintings can be expected to have vibrational modes like those of a model rectangular diaphragm, held under tension at the edges. But the effect of individually applied oil paints contribute to the

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anisotropic response of each artwork to vibrational excitation. Because the chemical and mechanical properties of different pigment particles, suspended in oxidizing oils such as linseed, walnut and poppy seed oils vary greatly, mechanical characteristics such as weight, MOE, tensile, compression, sheer and torsional strength of paint layers likewise vary greatly from color to color and brushstroke to brushstroke.

As a result of these variations in materials, vibrations experienced in handling and during road and air transit, at or near the resonant frequencies of a painting, result in idiosyncratic deterioration of cohesion within the paints and adhesion to the canvas below. These damages manifest as cracks through paint layers, cleaving and lifting paints from the underlying canvas, paint losses and other mechanical forms of deterioration. These fractures through previously continuous paint layers result in altered and measurable vibrational responses.

Despite these types of adhesion failures within paint layers, evidence of damage may not have completely manifested visibly on the surface of the painting. Aged, brittle, oxidized oil paints are the restraining layer in 100-year-old paintings and their isolated loss of cohesion and adhesion can be indicated by changes in displacement amplitudes and resonant frequencies detected using multipoint laser vibrometry. Likewise, measures taken by art conservators to repair fractured and cleaving paints inevitably stiffen areas where displacement amplitudes at damaged paints were formerly less retrained by the damage. These can likewise be measured to determine the effect of repair measures within the context of the surrounding undamaged original materials and structures.

The three paintings examined using MPV in this study were:

Fishhook from Hawaii, No. 2, 1939, an oil painting on canvas measuring 36 inches high by 24 inches wide. Collection: Museum of Fine Arts, Boston, Alfred Stieglitz Collection, Bequest of Georgia O'Keeffe, accession number 1987.540

Deer Skull with Pedernal, 1936, an oil painting on canvas measuring 36 inches high by 30 inches wide. Collection: Museum of Fine Arts, Boston. Gift of the William H. Lane Foundation, accession number 1990.432

In the Patio No. IV, 1948, an oil painting on canvas measuring 14 inches high and 30 inches wide. Collection of the Museum of Fine Arts, Boston. Gift of the William H. Lane Foundation, accession number 1990.434

Fig. 1 Above left, Fishhook from Hawaii, No. 2, 1939, collection: Museum of Fine Arts, Boston, 1987.540. Above center, Deer Skull with Pedernal, 1936, collection: Museum of Fine Arts, Boston, 1990.432. Above, right, In the Patio No. IV, 1948, collection: Museum of Fine Arts, Boston, 1990.434. © 2024 Museum of Fine Arts, Boston. Reproduced with permission.

History and structural characteristics of the paintings

Fishhook from Hawaii, No. 2, 1939 retains the original materials and structures used by the artist at the time of fabrication. The wood stretcher, commercially primed, fine weave, linen canvas, tacking edges and paints are essentially unaltered since leaving the artist's studio. A thin protective synthetic acrylic varnish was spray applied to the painted surface under O'Keeffe's direction after a light surface cleaning in 1948.Outside of occasional dusting and changes in framing materials, the painting remains as O'Keeffe originally presented it.

In this painting, O'Keeffe brush-applied a series of blue paints, light to dark in value, across the lower background and then spread and smoothed the paste-like paints with a palette knife in a manner like cake frosting. The result is a cured paint surface that is relatively thick but compliant to the vibrational behavior of the overall rectangular diaphragm. In a raking

light image, it is possible to see a series of parallel, lifted, vertical cracks in very light-blue paints, associated with the region of the first drum-mode response near the center of the painting. There are a series of similarly shaped vertical cracks in the viewer upper right quadrant. The somewhat concentric shape of some of the cracks in both areas suggest that both areas historically received a soft vertical press or impact on the front of the painting.

Deer Skull with Pedernal, 1936 is similar in size and orientation to the Fishhook painting, just 6 inches wider and painted just three years earlier. In contrast to the Fishhook painting, however, Deer Skull with Pedernal, 1936 is painted using single applications of color, with the twill-weave canvas texture generally visible under the paints. There is a carefully brushed vertical form representing a dead juniper trunk that runs generally through the vertical middle of the painting and horizontal forms near the bottom of the composition representing the New Mexico landscape adjacent to O'Keeffe's Ghost Ranch home.

Sometime between 1970 and 1976, in preparation for traveling exhibitions, the back of the painting was adhered to a secondary canvas using a heat activated adhesive mixture of natural resins and waxes, commonly referred to as a "wax resin lining." The goal of this lining was to flatten unsightly creases and secure cracked paints that had developed over the previous 40 years of travel and exhibition. Thus, this painting has two canvas supports, stretched over a new, heavy weight wood stretcher. It is thus stiffer, with more mass than the similar Fishhook painting. Oddly, the viewer right half of the painting has a noticeably thinner coating of the wax-resin adhesive on the verso or back of the canvas, than the viewer left side, which is thicker and likely heavier and stiffer.

In the Patio No. IV, 1948 is a much smaller, narrower rectangular painting. It is painted on a heavy linen canvas, with various mixtures of the iron oxide pigments raw and burnt umber, with white pigments to create values of light to dark and to add various degrees of opacity. In an interesting departure from her practice at the near mid-point in her professional career, O'Keeffe appears to have added a natural resin varnish to her initial brown-toned oil paints, possibly to achieve a highly matte, non-reflective surface. Using an imaging technique known as ultraviolet induced visible luminescence, we can see the characteristic greenish yellow glow of natural resin amendments at the beginning edges of many brush strokes. Additionally, we can see that O'Keeffe added a second layer of lighter overpaints across the viewer left side of the composition, resulting in a heavier, stiffer paint film in these areas, when compared to the viewer right side. The bright blue sky at the top of the painting is heavily amended with zinc oxide white, making that region more rigid when compared to the areas of brown paints.

In about 1958, this work was also adhered to a secondary canvas using a wax-resin mixture to repair a dent and gouge in the viewer lower left corner and two impact dents in the viewer right side of the composition. This treatment would add stiffness and mass to the canvas which, along with the smaller dimension, results in higher natural frequency responses, when compared to an unlined or larger format paintings.

Multi-Point Vibrometer (MPV) Components And Process Flow

The MPV system is a flexible and modular design consisting of a series of single point laser doppler vibrometers (LDV). The system can be configured based on the number of sensors required, frequency, amplitude, and modularity needed. As seen in Fig. 2, the system is configured based on application requirements. For this test, the system used consisted of 16 Polytec VibroGo LDVs each capable of measuring up to 100 kHz and 2 m/s. All systems were connected to a central data acquisition and communication box.

The controller has 3 input ports per sensor: ethernet, data acquisition, and power (Fig. 3). The ethernet port controls digital communication to change ranges, set bandwidth, autofocus the lasers, and provide any other communication controls to the laser. The analog BNC provides the selected data stream from the sensor. For this test, velocity was the chosen output but displacement and acceleration could have also been output. The power port allows all sensors to be connected to a common power source and one outlet.

For this test, the sensors were rows of 4 in a stair shape as seen in Figure 3. The first three rows had all 4 systems on a row mounted on one beam for easy movement and setup. The last row was on individual tripods to allow for flexibility on harder to reach points. All sensors were configured to be in complimentary IP Address networks and powered on. Each sensor was then aligned to the painting under test.The first eight sensors were connected to the lead controller. The second eight sensors were connected to the secondary controller. From each controller a USB cable and ethernet cable is run to a central laptop through a USB/Ethernet hub. The information flow thus described is demonstrated in Figure 4.

From the MDE control software, the sensors were autofocused, ranges optimized, and acquisition parameters were set. In a separate software (MDE), a geometry file was created that represented the orientation of the sensors as aligned on the painting. This geometry was then imported into the MDE software so that it could be applied to the data once collected. Once

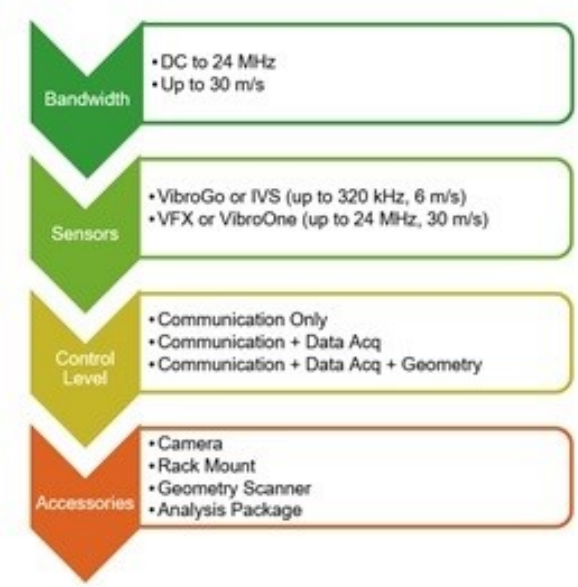

Fig. 2 System configuration options.

Fig. 3 MDE controller (left) and example test setup (right). © 2024 Museum of Fine Arts, Boston. Reproduced with permission.

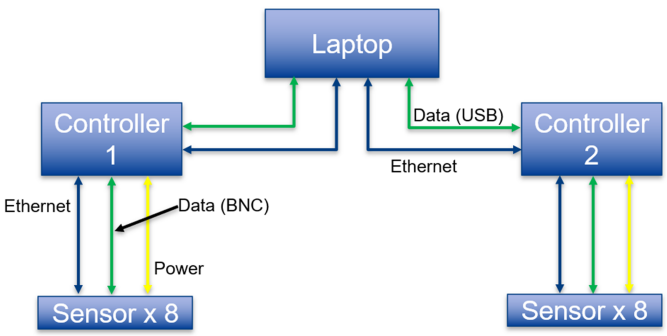

Fig. 4 Information flow and wiring diagram for multi-point vibrometer system.

all the parameters were set, the data was collected and monitored in the MPV software. Once data collection was complete, the data was combined with the geometry and available for analysis in an existing MPV analysis program. This program allows for any signal processing necessary including but not limited to filtering, FFT transformations, and data extraction. The process flow is pictorially described in Figure 5.

Fig. 5 MDE Process Flow.

Figure 6 show the software interface for the MPV software. This is the data acquisition portion of the software. Once the data is acquired, it is then exported to MDE software which handles the ODS analysis and further post-processing.

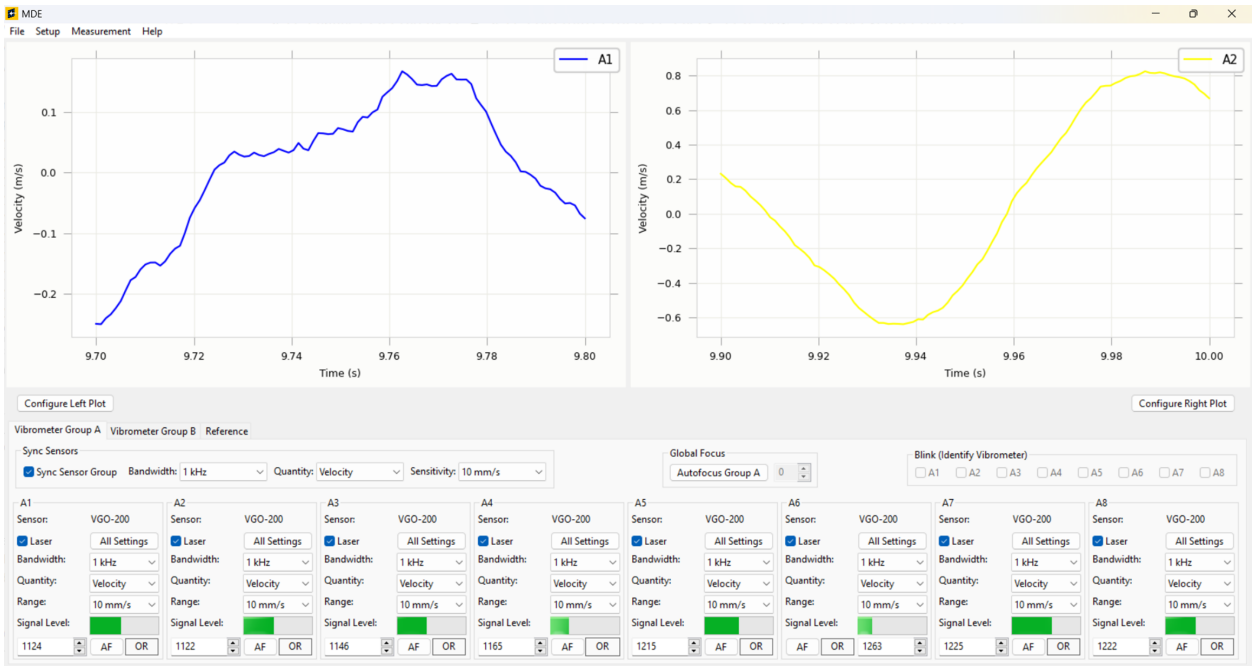

Fig. 6 MDE software interface. Top left and right: example measurements from two different sensors. This portion of the interface is configurable. Bottom: Vibrometer settings for one set of 8 sensors.

Measurement Results And Analysis

The MPV data user interface provides a dynamic presentation of a painting's response to vibration excitations across a range of frequencies selected in the FFT frequency domain. This makes it possible for conservators to evaluate displacement and velocity amplitudes across a work and identify idiosyncratic responses where there may be damage or repairs.

MPV analyses provided important insights for all three of the tested paintings. For example, the smallest painting, *In the Patio IV*, 1948, has the highest natural frequency of the three paintings at 11.4 Hz, (Fig. 7). The full spectrum response shows that most of the response is below 100 Hz and primarily below 50 Hz (Fig. 8). A previously repaired vertical crack, near the center of the painting and to the right of the central, rectangular door form, showed a stiffer response when compared to the areas immediately adjacent to the left, which exhibited displacements approximately four times as great. (Fig. 9). This indicated that this crack repair remains secure and has not re-opened.

Deer Skull with Pedernal, 1936, (Fig. 10) has a vibration response that is rather typical of a large canvas painting (Fig. 11), with a natural frequency at 8.6 Hz (Fig. 12). At this frequency, the center of the painting is highly compliant and exhibits displacement and velocity magnitudes 8 times greater than the surrounding edges, which are restrained by being secured to the surrounding wooden stretcher. Above the center of the painting, the painted skull form, outlined by top-most, central MPV reference points (Fig. 13), is painted predominantly in lead carbonate white, a paint that results in a very stiff, cured, oil paint layer. As might be expected, the velocity and displacement of the area covered by the stiff skull paints are like

those seen at the retrained edges of the painting. Additionally, at 13.5 Hz, 23.67 Hz and of 26.1 Hz, a vertical displacement can be seen along the richly textured, brown and black paints of the dead juniper trunk form that runs vertically down the center of the painting, (Fig. 14). Also interesting is the fact that vertical cracks though the paints, repaired by the 1970's era lining project, have preferential vibrational displacements at around 16 Hz, (Fig. 15) with greater displacement and velocity amplitudes than the areas immediately below them. These displacements may indicate fatigue failures in the 1970's repairs at these two locations.

In contrast, *Fishhook from Hawaii*, No. 2, 1939, (Fig. 16) has a very idiosyncratic vibrational response, despite its similar size. For this work, the artist selected a very fine weave, linen canvas, exhibiting a natural frequency of 10.3 Hz, (Fig. 18). Because of the greater density of canvas thread crimps, and because it has a slightly stiffer white priming layer under the paints, the painting exhibits a higher natural frequency than that of Deer Skull with Pedernal, 1936. What is most interesting is that *Fishhook from Hawaii*, No. 2, 1939 has a series of fatigue creases and cracks through the priming layers and paints at the top-center and lower left- and right-side edges. Even though the edges of a canvas painting are generally the most restrained and therefore the least compliant, being immediately adjacent to the edge where the canvas is tacked to the side of the stretcher frame, the canvas and paints at these cracked regions exhibit the greatest displacement and velocity, six-times greater than the grid points on the edges immediately above and below the actively cracking areas. In addition, the shape of the of the edge displacements along the viewer right edge preferentially extend upwards and to the right, directly into a series of vertical cracks through the paints that were discovered slightly below, and to the left of the fishing line swivel figure in the painting. These cracks can be seen when the painting is viewed in strongly contrasting raking light (Fig. 19).

Conclusion

The condition of a work of art is influenced by its materials, history, and environment. Conservators use various techniques to understand and protect these complex objects. Laser Doppler vibrometry offers a non-destructive, non-contact way to assess a painting's mechanical responses to vibration excitations, which can illustrate and document both general natural frequency responses and idiosyncratic characteristics that can detect the existence of isolated damage or reflect the ability of previous repairs to ensure structural continuity with the surrounding surfaces. Benefits of vibrometry include but are not limited to:

- Non-contact measurement: Avoids physical contact, preventing potential damage to delicate artworks.
- High sensitivity: Detects even subtle vibrations that could lead to long-term deterioration.
- Wide frequency range: Measures vibrations across a broad spectrum, capturing both low-frequency and high-frequency components.
- Real-time analysis: Provides immediate results, allowing for timely intervention if necessary.

For priceless artworks, vibrometry offers a valuable tool for the detection and monitoring of damage and deterioration. By identifying potential vulnerabilities, conservators can take steps to isolate works from damaging resonant frequencies in handling and transit. Moreover, detection of isolated, idiosyncratic vibrational responses across a work of art can help

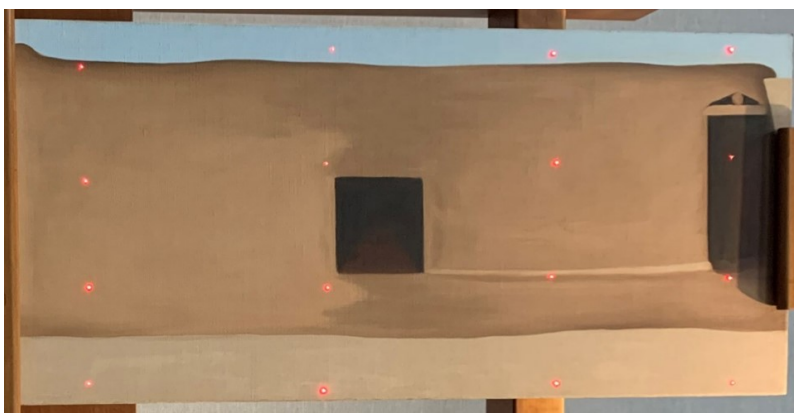

Fig. 7 Painting with measurement locations – 16 locations in total. *In the Patio IV*, 1948.

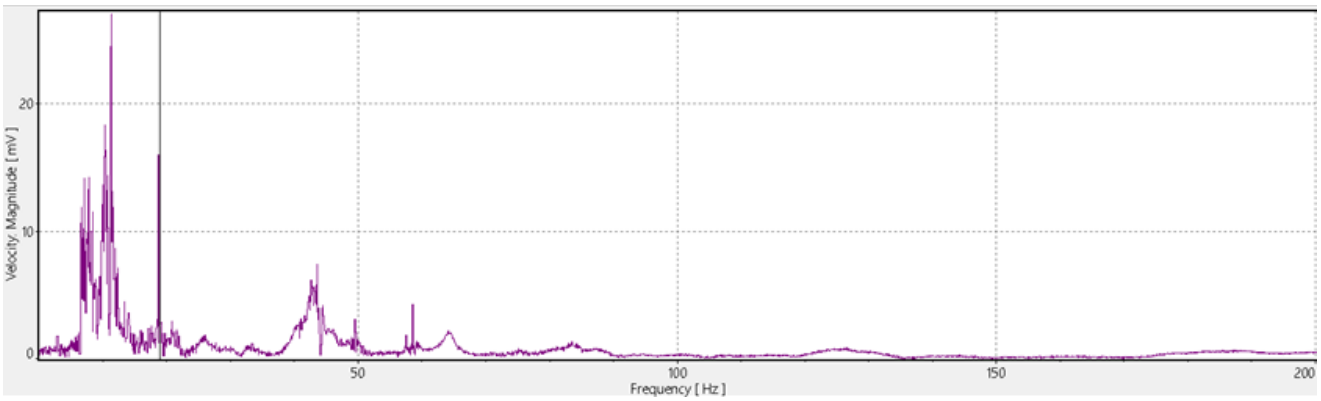

Fig. 8 Average frequency spectrum of *In the Patio IV* over all points measured. The sensitivity for the spectrum is 5 mm/s/V.

conservators detect and identify fatigue failures in materials and structures early in their development. Likewise, early detection provides greater opportunity for stabilizing conservation treatments. Following treatment, a work can be re-measured to both ensure that the repair has been effective in creating a more continuous vibrational response across the damaged area and makes possible periodic inspections of the work to monitor the life of the repair over time.

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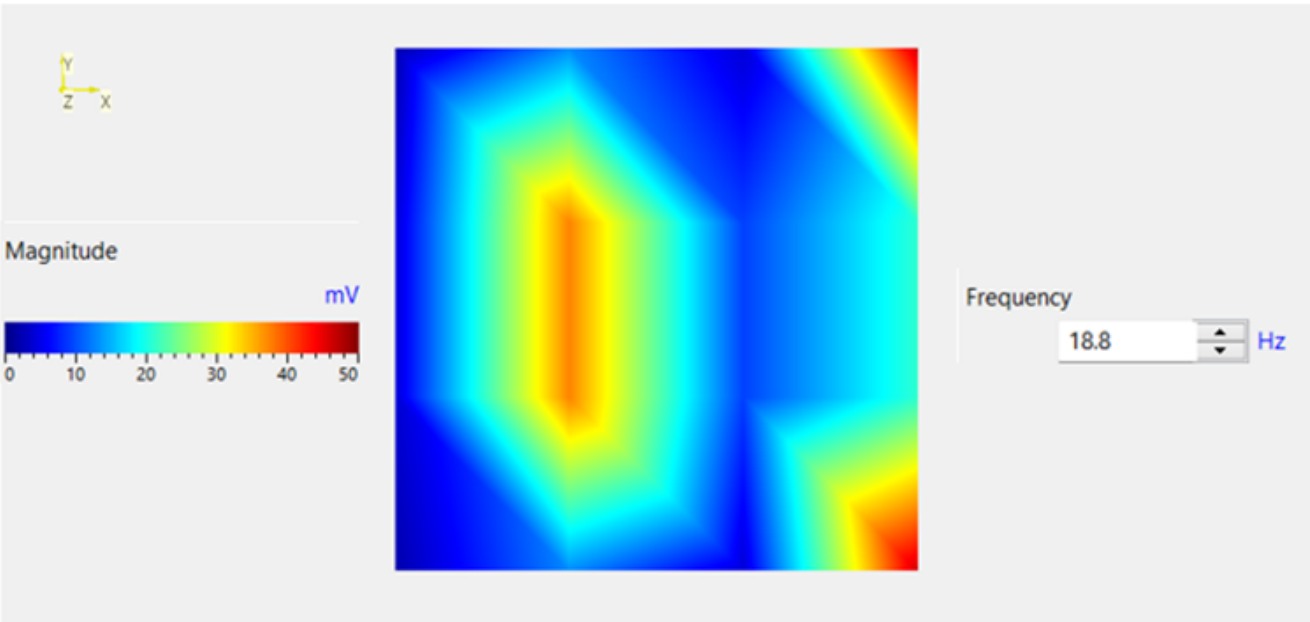

Fig. 9 Operation deflection shape indicating the effect of a repaired crack. This is manifested by a 4x increase in displacement. The sensitivity for this deflection shape is 5 mm/s/V.

Fig. 10 Painting with measurement locations – 16 locations in total. *Deer Skull with Pedernal*, 1936.

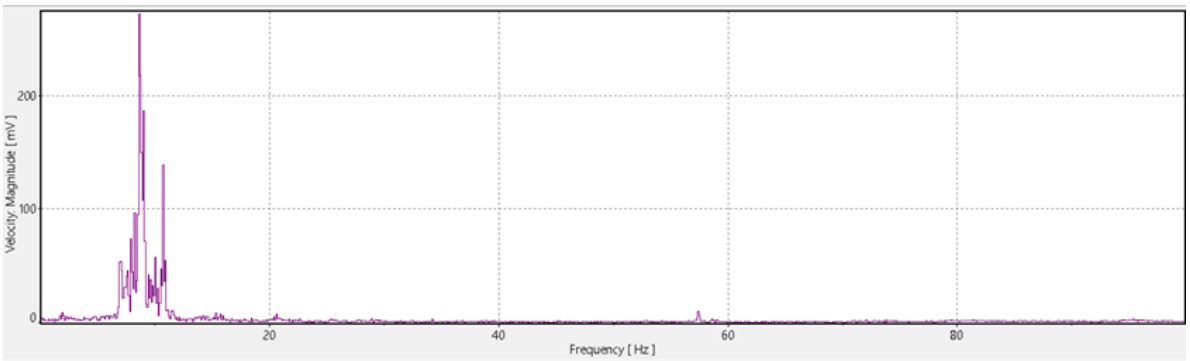

Fig. 11 Average frequency spectrum of *Skull with Pedernal* over all points measured. The sensitivity for conversion is 2.5 mm/s/V.

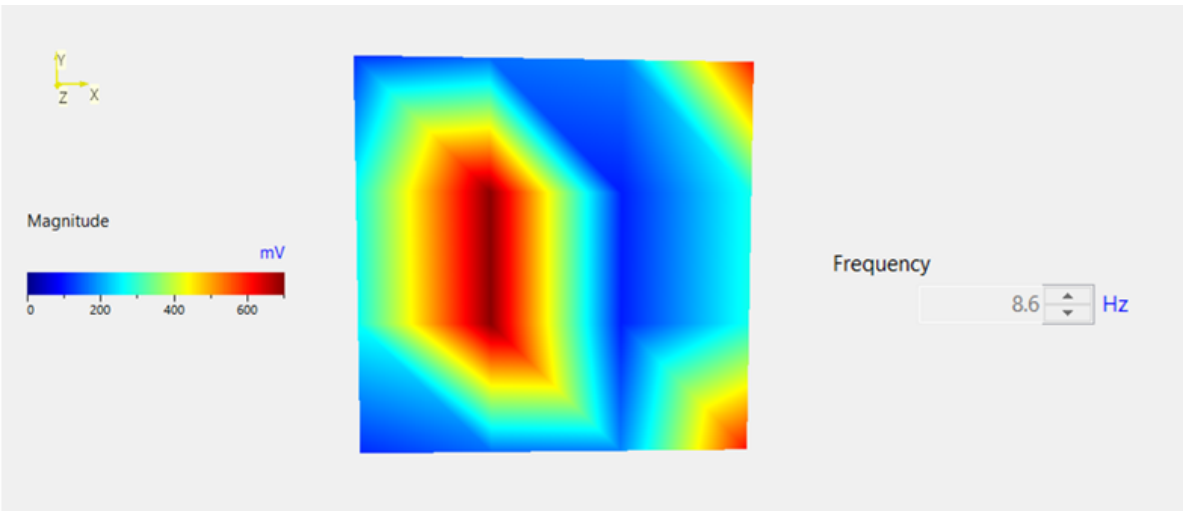

Fig. 12 First natural frequency. *Deer Skull with Pedernal*, 1936. The sensitivity for this deflection shape is 5 mm/s/V.

Fig. 13 Top portion of the painting done using lead carbonate white, explaining the increased stiffness in the response. *Deer Skull with Pedernal*, 1936.

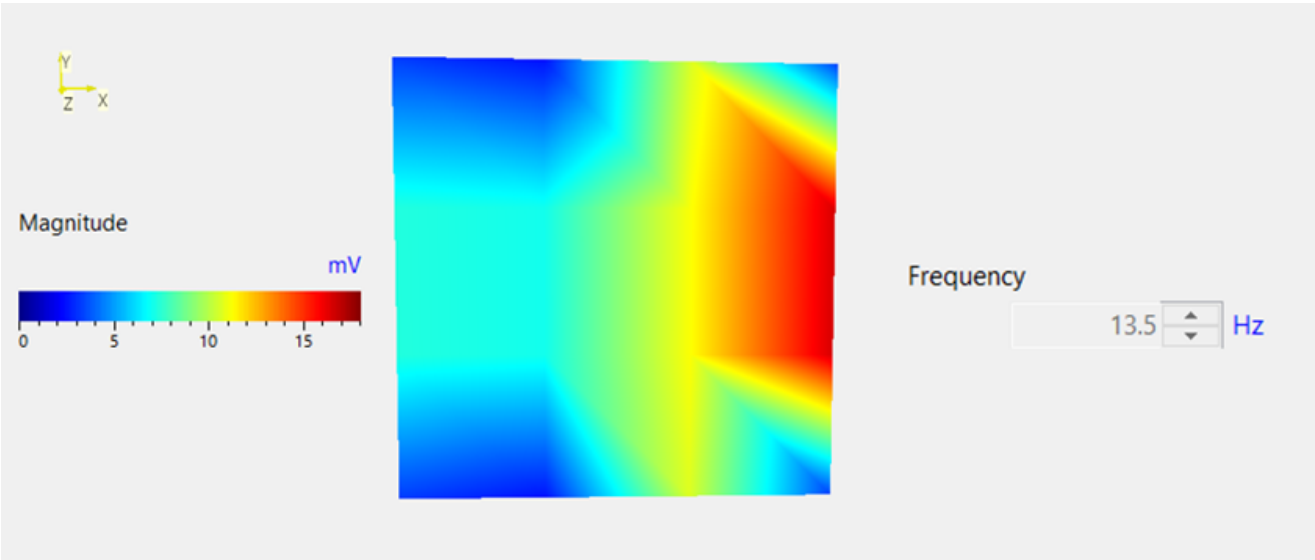

Fig. 14 Vertical "band" of displacement manifested because of the paint use. *Deer Skull with Pedernal*, 1936. The sensitivity for this deflection shape is 5 mm/s/V.

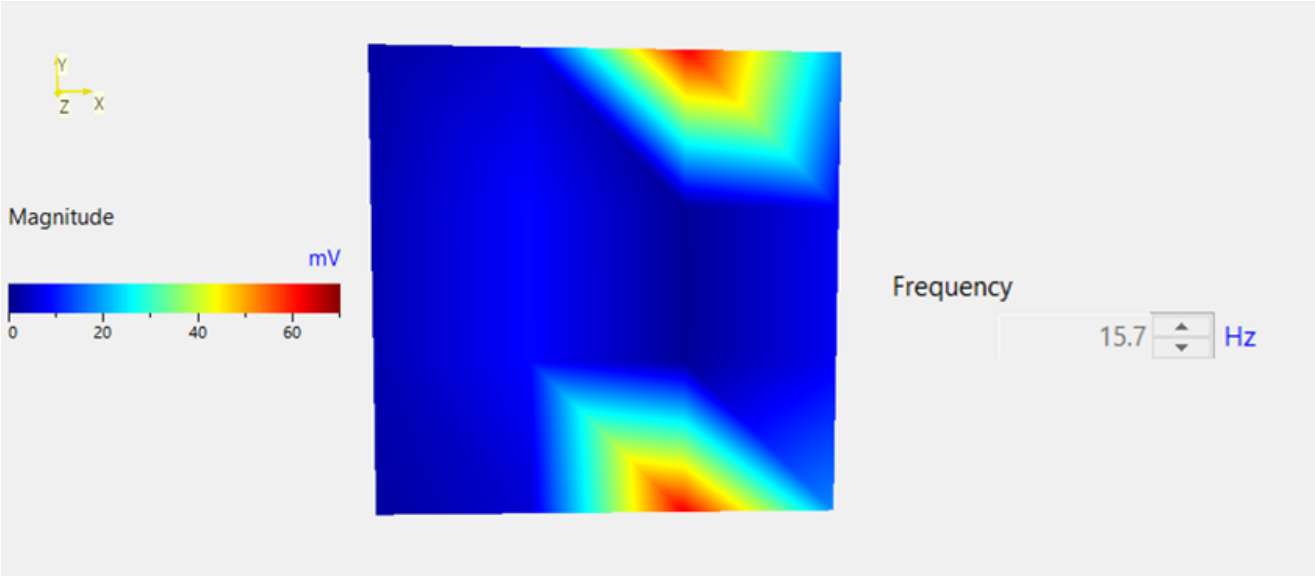

Fig. 15 Efficacy of the crack repair project. Asymmetric displacement reflects the differences in the quality of repair. *Deer Skull with Pedernal*, 1936. The sensitivity for this deflection shape is 5 mm/s/V.

Fig. 16 Painting with measurement locations – 16 locations in total. *Fishhook from Hawaii*, No. 2, 1939.

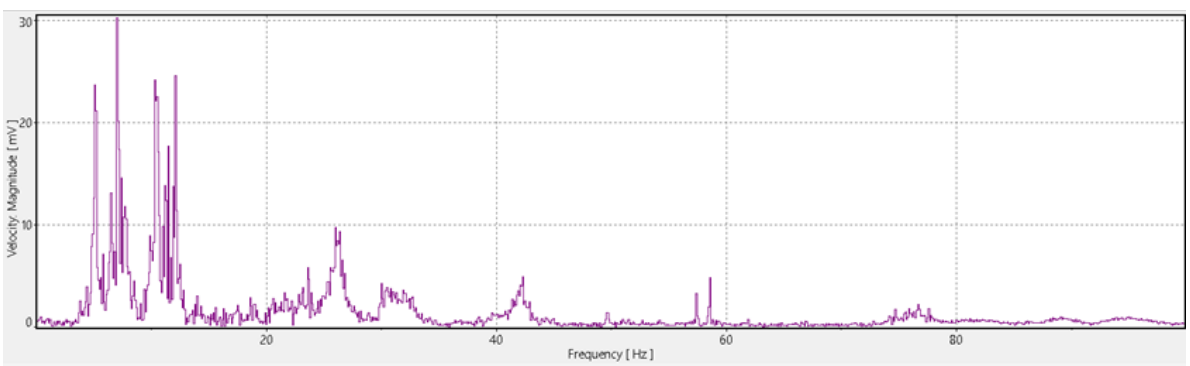

Fig. 17 Average frequency spectrum of *Fishhook from Hawaii* over all points measured. The sensitivity for conversion is 5 mm/s/V.

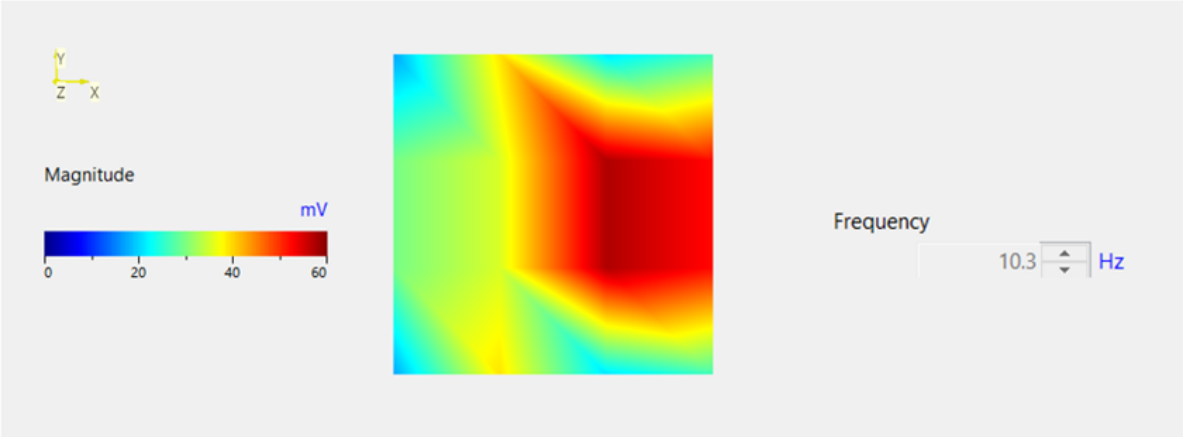

Fig. 18 First natural frequency. *Fishhook from Hawaii*, No. 2, 1939. The sensitivity for this deflection shape is 5 mm/s/V.

Fig. 19 Cracks definition resulting in preferential, non-linear displacement response, especially at the edges.