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NONDESTRUCTIVE EVALUATION OF WORKS OF ART

A. Murray, R. E. Green, M. F. Mecklenburg, C. M. Fortunko

ABSTRACT: *The presence of cracks and flaws in the wood support of panel paintings present a potential hazard to the transportation of these objects. Unfortunately, many of these defects are not easily visible and assessing the transport risk of panel paintings is difficult. Several different nondestructive testing techniques are examined and evaluated in terms of their crack detection sensitivity as well as ease of use. One method, xeroradiography, shows promise in its ability to detect extremely small cracks using equipment compatible to that typically found in conservation laboratories.*

INTRODUCTION

The safe transportation of a panel painting is contingent on its internal integrity. Various nondestructive methods are being investigated and developed to detect voids, hidden cracks, and fine fractures in such paintings. These methods could be incorporated into the repertoire of techniques from which conservators draw to prevent the premature failure of objects as a result of such flaws. Computer analysis shows that cracks in wood promote severe stress concentrations that are aggravated by the mechanical constraints imposed by the construction of a panel painting.[1] The panel's structural condition must be mapped nondestructively in order to predict how it will respond mechanically over time or in different environments. Decisions can then be made on whether the object can be safely shipped to special exhibitions, and plans can be made for proper display, storage conditions, and conservation treatments. We have demonstrated the nondestructive evaluation capabilities of various techniques by examining standard panels of wood and actual panel paintings.[2] The standard "mock" panel paintings were made of white oak (*Quercus* sp.), tulip poplar, hard maple (*Acer* sp.), true mahogany (*Swietenia* sp.), black cherry, and western fir (*Abies* sp.). These panels contained voids of between 0.15 and 0.6 cm (0.059 and 0.2 in.) in diameter and cracks smaller than 0.02 cm (0.008 in.). The techniques for investigation included: x-ray radiography, xeroradiography, and ultrasonics. Results show that both x-ray radiography and xeroradiography, can easily find voids at least as small as 0.15 cm (0.0059 in.). Xeroradiography has the advantage, however, because its edge enhancement property enables flaws to be displayed prominently. At certain angles, cracks less than 0.02 cm (0.008 in.) were easily seen. The results of using these two techniques on a panel painting are discussed and compared below. Ultrasound techniques using an *all-air coupled system* and a *hybrid air-coupled/dry-coupled system* have shown encouraging preliminary results in finding voids and cracks.

The deterioration of panel paintings has been of interest for many years.[3] Panels become dimensionally less stable with changes in relative humidity, especially when they have been thinned and restrained during "conservation treatments." It is well known that by maintaining the relative humidity constant, the lifetime of these works of art will be prolonged. The studies being discussed at this conference are examining the risk caused by improper traveling conditions.

To determine whether panel paintings should be transported, it is important to ascertain their condition. The many techniques included in nondestructive testing enable the risk to be assessed. A panel painting may include many layers;[4] however, it is the condition of the wooden support layer that is the focus of this paper.

The structure of wood is well known.[5] The anomalies that exist naturally or that may evolve need to be studied to understand results from different nondestructive evaluation (NDE) techniques. Natural inhomogeneities in wood include seasonal growth rings, knots, and ray cells, which are sheets of cells that grow in a radial direction along the longitudinal radial axis of the tree. Voids are often created by insects, including the common furniture beetle, (*Anobium punctatum* in the anobiidae family), the death-watch beetle (*Xestobium rufovillosum*), the powder-post beetle (Lyctidae), termites, and ants.[6] The tunnels can be as small as 0.1 cm (0.04 in.) and can result in a completely riddled panel. The panel is then weakened, allowing cracks and breaks to occur more easily. Cracks also appear in panel paintings because of changes in the relative humidity that cause dimensional changes.[7] When restrained, wood compresses with water adsorption, crushing wood cells. Wood develops tensile stress and cracks with desorption. The structure of wood leads to severe anisotropic behavior as the dimensional changes are greater in the radial and tangential directions than in the longitudinal direction. Both the adsorption and desorption of water can, therefore, lead to warping and splitting of the wood. The expansion and contraction of the wood can also cause the ground and paint layers to crack, cleave and buckle if they are not flexible.

The wood industry has used a variety of nondestructive techniques (NDT) including: visual tests, ultrasonics, stress-wave measurements, vibration tests, x-ray radiography, computer aided tomography (CAT), collimated photon scattering, magnetic resonance imaging (MRI), acousto-ultrasonics (AU), acoustic emission (AE), microwaves, pulsed electric current, and even sniffer dogs. Many industrial x-ray studies have been concerned with wood-boring insects. Ultrasonics has been compared with other methods to determine quality, strength, elastic constants, and degree of deterioration of wood. The theory, experiments, and viabilities have been discussed in many articles and proceedings.[8]

The museum conservation field has used many different nondestructive techniques on many materials. A few examples include: x-ray radiography,[9] which has been used extensively; xeroradiography,[10] on ceramics, porcelain, Egyptian faience, and underdrawings of paintings; ultrasound,[11] on murals, masonry, and wetted archaeological woods; infrared thermography,[12] to find deterioration in wooden panel paintings; x-ray computer tomography;[13] visible light; ultraviolet radiation; and other techniques. The first three techniques, x-ray radiation, xeroradiography, and ultrasound with various coupling techniques, have been used in this study. Previous work has shown infrared thermography to have only limited success in finding voids deeper than 0.6 cm (0.2 in.) from the surface of the wood. More progress has been made in discovering delaminations between the upper layers of panel paintings and in marquetry panels with infrared radiography.[14] Before this work, x-ray radiography and xeroradiography had not been compared while trying to map out the voids and cracks found in panel paintings; work with xeroradiography has been performed at the Canadian Conservation Institute and other institutions. Air-coupled and dry-coupled ultrasonic systems have not been used on wooden panel paintings or on other art objects.

The air-coupling technique provides an alternative to the conventional coupling methods. Coupling is needed between the transducers, the source of the ultrasonic wave, and the object to match the acoustic impedances, thereby allowing the ultrasonic wave to be transmitted through the material. Air is very difficult for the high-frequency wave (MHz) to traverse, but, water, oil, and grease are not.[15] Industry has been able to make use of ultrasound because of its more lenient requirements of acceptable coupling. Often the object may be submerged in a water tank. Removable oils or greases are used, but may leave a residue. Special polymeric films have been used to couple, but a great amount of force needs to be used to maintain the couple. Rolling transducers, which use a polymeric film, do not provide a constant pressure. None of these coupling methods is safe enough to use on museum objects. The newer method of coupling, with special air-coupling transducers, has shown promise in overcoming these problems.[16] Of course, the technique of ultrasound is only in its preliminary stages, as the ultrasonic waves will be altered by the many inhomogeneities of wood discussed above. Thus, the results require careful interpretation. Work is now in progress to address this.[17] The potential dangers of insonifying objects also needs to be examined.

EXPERIMENTAL PROCEDURE

Samples

The samples used throughout the experiments were six panels of wood, each with dimensions 40 x 23.5 x 3.5 cm^3 (16 x 9.3 x 1.4 $in.^3$). The six species of wood, with their densities[18] are:

white oak (*Quercus* sp.) (720 kg/m^3 or 0.0260 $lb./in.^3$),

tulip poplar (460 kg/m^3 or 0.0166 $lb./in.^3$),

hard maple (*Acer* sp.) (660 kg/m^3 or 0.0238 $lb./in.^3$),

true mahogany (*Swietenia* sp.) (545 kg/m^3 or 0.0197 $lb./in.^3$),

black cherry (530 kg/m^3 or 0.0191 $lb./in.^3$),

and western fir (*Abies* sp.) (410 kg/m^3 or 0.0148 $lb./in.^3$).

Results from the white oak and tulip poplar panels will be shown here as the other results have been reported previously. The panels were at approximately 12% moisture content.

To simulate voids and flaws in the panels, holes of different diameters (0.6, 0.4, 0.35, 0.2, and 0.15 cm [0.2, 0.16, 0.14, 0.08, and 0.059 in.]) were drilled into the sides of the panel at different depths from the surface, as shown in Figure 1. The holes closest to the surface were between 0.2 and 0.5 cm (0.08 and 0.2 in.) from the surface, the next closest were 1.0 cm (0.39 in.), and the furthest away were between 1.5 and 2.0 cm (0.59 and 0.79 in.) from the surface. On each side, a solitary 0.35 cm (0.14 in.) diameter hole was drilled 1 cm (0.4 in.) from the top surface. The cracks of different sizes and lengths in the sample

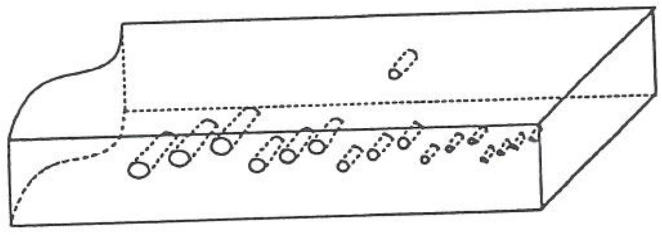

FIGURE 1
Angled view of half a wooden panel containing voids.

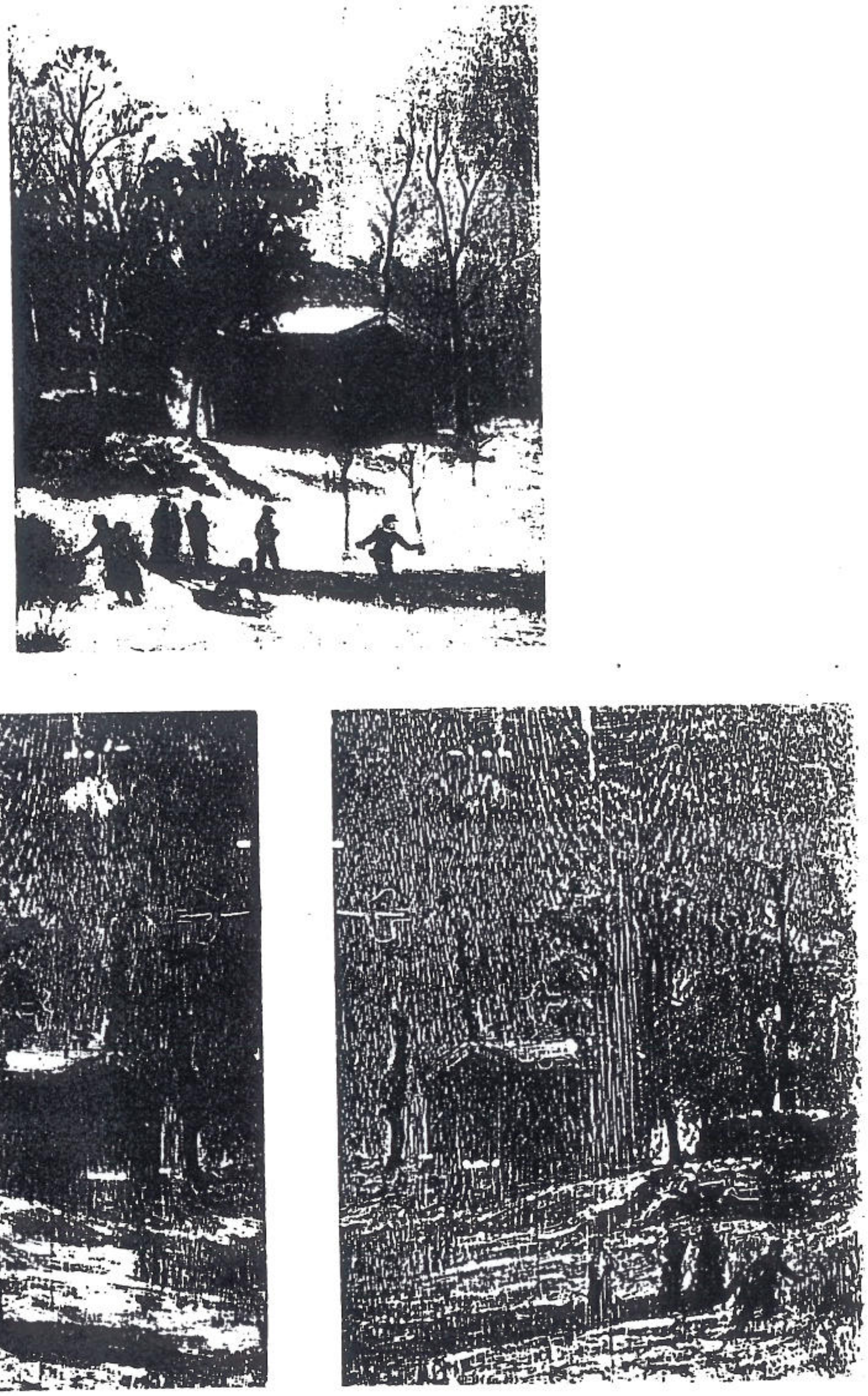

FIGURE 2
Panel painting: (a) photograph (b) x-ray radiograph (c) xeroradiograph. The image produced by xeroradiography is the mirror reflection of the original because of the processing method.

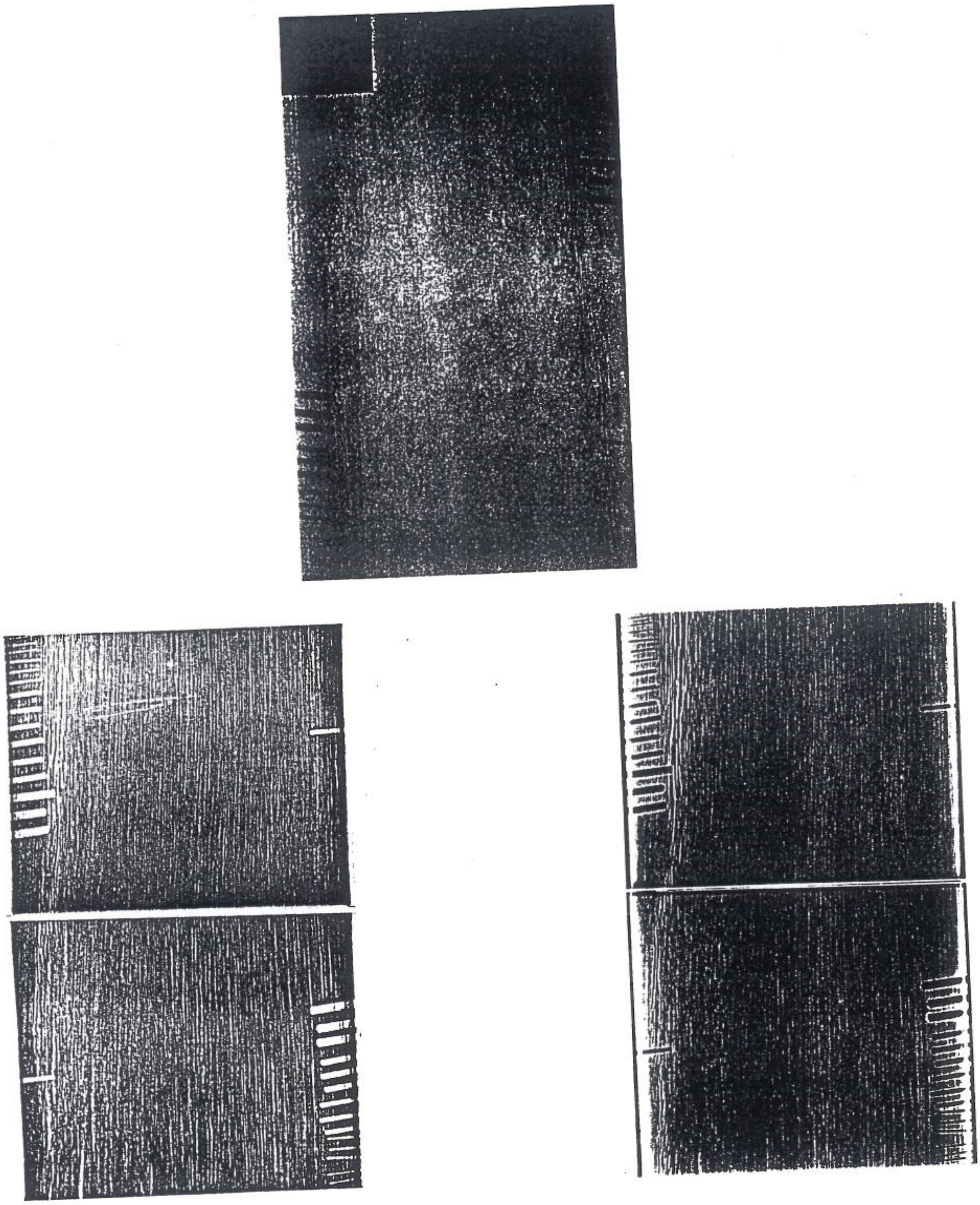

FIGURE 3
Panel of white oak: (a) x-ray radiograph (b) positive xeroradiograph (c) negative xeroradiograph (mirror image).

panels of white oak, hard maple, true mahogany, and western fir occurred naturally from swings in relative humidity.

An oak panel painting, probably made around the turn of this century, (Figure 2a) was x-ray radiographed and xeroradiographed (Figures 2b and 3c). The width and length of the panel were 20 x 30 cm^2 (7.9 x 12 $in.^2$) respectively. The thickness was 0.7 cm (0.3 in.) at the edges, tapering to 1.2 cm (0.50 in.) in the center. This panel had a number of cracks along the grain, at the top and bottom edges of the panel (less than 0.1 cm or 0.04 in.) and some voids (around 0.1 cm or 0.04 in. in diameter). As this painting is part of a research collection at the National Gallery of Art in Washington strain gauges and metal wires had been attached to the back for another set of experiments. These gauges and wires are visible on the radiographs. The painting shows a winter scene of a house surrounded by trees with eight figures at the bottom. The pigment had been laid directly onto the wooden oak panel. A white pigment was used often, for example in the areas surrounding the figures, the house, and the trees. This allowed the picture to be seen on the radiographs.

Techniques

Each panel was x-ray radiographed with softer x-rays than in previous work, for results which were clearer and had more even contrast. The white oak panel is shown in Figure 3a. The top left-hand corner of the wooden panel had been removed for another set of experiments, before the x-ray radiographs and after the xeroradiographs were taken. A Dynarad 150 unit from Philips Electronic Instruments TORR was used. The settings used were 30 kV, 5 mA, and 20 minutes. The distance from the tube to the film was 209 cm (82.0 in.). The film (Kodak M industrial large) and a 0.1 cm (0.04 in.) sheet of lead, which lay under the film, were placed in a vacuumed envelope. Each wooden panel was xeroradiographed. A positive and a negative image of the white oak panel are shown (Figure 3b and c). A XEROX® 125 System was used. The plate could image only half of each panel with some overlap, therefore two images needed to be taken for each panel. This caused the horizontal line seen in the xeroradiographic image. For the positive images, the settings were 42 kVp, 300 mA, for 0.4 seconds. For the negative images, the settings were 44 kVp, 300 mA, for 0.3 seconds. The panel painting was x-ray radiographed at the National Gallery of Art, Washington using the settings 25 kV, 50 mA, for 12 seconds. The xeroradiographs of the painting were taken using the same equipment as for the wooden panels and the settings 45 kVp, 10 mA, and 0.2 seconds. Both radiographs were taken from the front of the painting (Figure 2b and c).

The first ultrasonic setup used an all-air coupled configuration (Figure 4). The transducers could be positioned anywhere over the tulip poplar panel. A unipolar, burst pulser (3 W impedance, 450 V) generated the signal, which was then sent through an impedance-matching network (high-pass inverter). Both air transducers were 0.5 MHz, with 2.5 cm (1.0 in.) diameter face-plates and 5.1 cm (2.0 in.) focal lengths. They were both 2.0 cm (0.80 in.) away from the sample and were therefore defocused on the sample. They were also offset by 1.3 cm (0.50 in.) along the horizontal axis. One transducer sent the signal through the sample and the other received it after it traversed through the sample. The signal was then sent through a very low-noise bipolar amplifier, two precision attenuators (12 x 10 dB and 12 x 1 dB), a band-pass filter, and a linear detector. The transducer-transducer spacing was fixed by a "U-shaped" holder. The second setup was a hybrid air-coupled/dry-coupled through-transmission configuration on the white oak panel. The setup was identical to the previous one, however, the signal was transmitted through an air-coupled transducer (0.5 MHz, 2.5 cm or 1.0 in. diameter, 5.1 cm or 2.0 in.) focal length, and 2.3 cm or 0.90 in. from the surface) and was received by a dry-coupled transducer (ULTRAN WD 50-1, 113065, 0.5 MHz, and 0.953 cm or 0.375 in. diameter). Scissorlike tongs were used to hold the transducers. Both ultrasonic setups have been described in previous work.

EXPERIMENTAL RESULTS

The results showed that all voids were clearly seen with both radiographic techniques. The xeroradiographic technique displayed cracks at the bottom left-hand corner of the white oak panel, which were 0.06 cm (0.02 in.) at the widest point and 0.02 cm (0.008 in.) at the smallest point. Grain variations are better recorded with the xeroradiography. Results from the hard maple panel show that cracks smaller than 0.02 cm are clearer with xeroradiography than with the x-ray radiography. Other anatomical features of wood that are better shown with xeroradiography include grain variations (visible in Figure 3b and c), knots (of which both live and dead could be distinguished), mineralization pockets, and cutting defects; the last three have been shown in previous work.

The xeroradiographic images of the panel paintings showed cracks (less than 0.1 cm or 0.04 in.), voids (around 0.1 cm or 0.04 in. in diameter), vessel lines in the wooden support, and the white pigment (Figure 2). There appear to be two types of cracks, both less than 0.1 cm (0.04 in.); one at the top edge of the painting with an increase in density (a light line) and one at the bottom edge of the painting with a loss of material (a dark line). The cracks with an increase in density were probably in the wood prior to its painting and then filled up with the paint. The other cracks, which showed a decrease in density, were probably formed after the painting of the panel. The x-ray radiographs do not show the cracks as clearly. The voids, approximately 0.1 cm in diameter, were filled with pigment and, therefore, now show an increase in density. The strain gauges and wires appear on the left-hand side of the image, in the center above the roof in the painting, and on the lower right-hand side above the figures.

In the x-ray radiographic image, the pigment plays a greater part; more levels of gray are included than indicated in the xeroradiograph. This effect may be due to the differ-

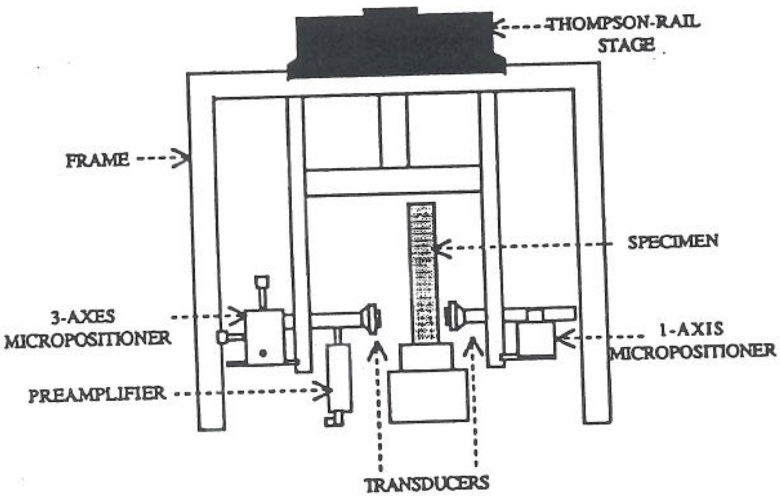

FIGURE 4
Experimental configuration of all-air-coupled ultrasound.

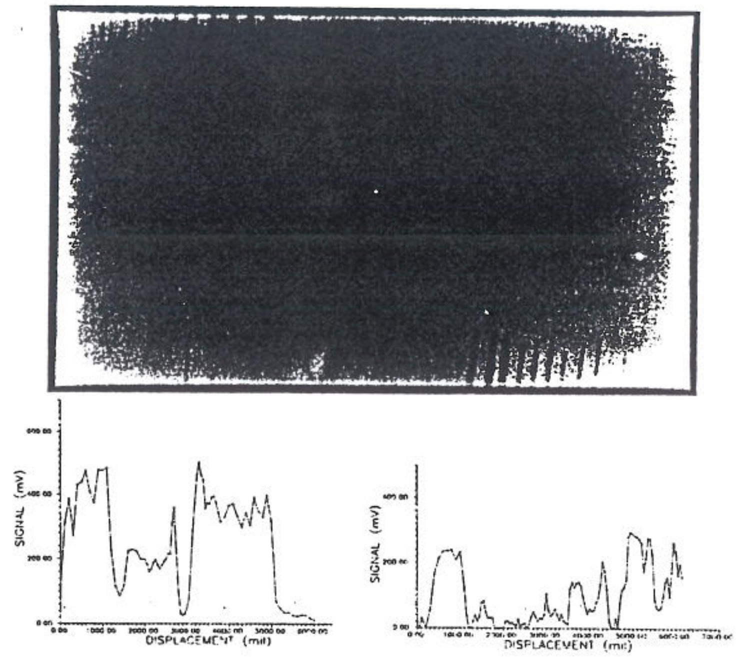

FIGURE 5
Results from all-air-coupled ultrasonic technique performed on tulip poplar.

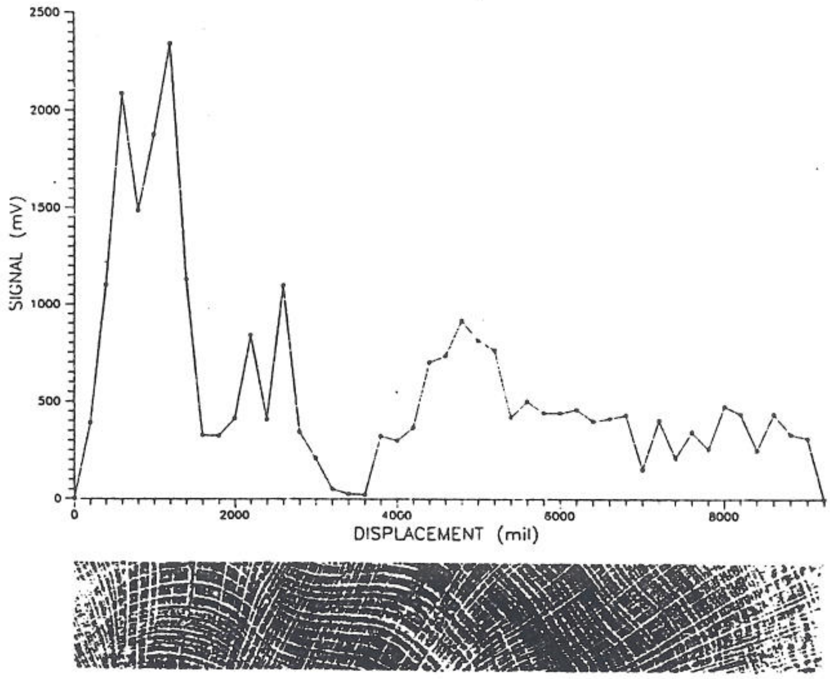

FIGURE 6
Results from hybrid air-coupled/dry-coupled through-transmission ultrasonic technique performed on white oak.

ence in kilovoltages used; that of the xeroradiograph is almost two times as powerful, so that the xeroradiograph is not as influenced by the pigments. This makes the x-ray radiographs more difficult to interpret if the pigments hide what is of interest, which in this case, is the condition of the wooden support. For example, the extent of the crack at the center of the bottom edge of the panel painting is clearer on the xeroradiograph than on the x-ray radiograph, where the image is as dark as the crack and therefore hides the end of the crack. Note that not all the figures on the painting appear on either radiograph, most likely because of the different pigments used.

When using the all-air coupled ultrasonic system, various sections of the poplar panel were analyzed along a straight line, approximately one inch from the bottom edge, over the holes (Figure 5). Pieces of lead tape were placed onto the sample to give a reference for the analysis (not shown in x-ray radiograph). On the left-hand graph, the tape was placed at 1,400 mil and after 5,000 mil and for the right- hand graph, it was placed before 500 mil. Distinct decreases in signal occur over the solitary holes and over the pieces of lead tape. Over areas with many voids of different diameters and depths, the transmitted signal is smaller where there are larger diameter voids and less signal is allowed through, while the signal is larger where the voids are smaller and more signal is allowed through. Other results show that the signal is greater over areas where the beam is not skewed by the grain of the wood. Gradual decreases correspond to changes in grain.

The all-air coupled ultrasonic system worked for the lower density of tulip poplar, but not for the higher density woods such as white oak. This may be improved by using different transducers. Only the higher density woods had cracks and therefore to evaluate these types of voids, a different system, the hybrid air-coupled/dry-coupled system, had to be used. The results (Figure 6) show definite signal decreases around 1,600-2,200 mil and around 3,200-3,600 mil, corresponding to cracks, which were as small as 0.1 cm (0.04 in.). There is also a strong correlation between signal size and the direction of the grain. There is a larger signal over areas where the grain is perpendicular to the edge of the sample. The opposite is also true. Any analysis using ultrasound to discover flaws will have to consider grain orientation, which causes beam skewing, and any other artifacts within the wood. Resolution may be adversely affected and other information about the sample may get hidden because of speckle caused by the inhomogeneities in the wood.

CONCLUSION

The x-ray radiography and xeroradiography detect the voids with the smallest diameter (0.15 cm or 0.059 in.), at all depths from the surface of the panels; the edge enhancement in the xeroradiograph technique does, however, make voids more visible. The xeroradiographic results also show the smallest cracks in the panels (less than 0.02 cm or 0.008 in.), which were not always clear in the x-ray radiograph. The other flaws, including knots (both live and dead), grain, and cutting defects, were more easily discernible with xeroradiography. This technique was able to show flaws in actual panel paintings and differentiate between the flaws that had occurred before and after painting the wooden panel. Either a positive or a negative xeroradiographic image may be more useful according to what the individual researcher is used to and why the artifacts are being viewed. It is, therefore, valuable to take both images. X-ray radiography remains a more easily accessible technique, but clearly is not as useful as xeroradiography.

The two ultrasonic systems have given promising preliminary results in showing cracks at various angles that cannot be detected with x-ray radiography and xeroradiography. Another situation that could benefit from using ultrasound occurs when the pigment does not allow the x-ray beam to penetrate the paint layer at all, so that the flaws within the wooden support layer cannot be found. The conventional coupling problem, that of matching acoustic impedances without causing harm to the object being examined, has been overcome using these systems. The all-air-coupled system is useful on lower density wood such as tulip poplar and distinguished voids as small as 0.15 cm (0.059 in.) in diameter. The hybrid air-coupled/dry coupled technique was able to map out the cracks of higher density woods, such as white oak. The system was able to show cracks of 0.1 cm (0.04 in.). □

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NOTES

1. Marion F. Mecklenburg, private communication, current research work ongoing at the Conservation Analytical Laboratory, the Smithsonian Institution.

2. In this paper, the term "previous work" refers to these two papers: Alison Murray, "The Nondestructive Evaluation of Wooden Art Objects," (M. S. in engineering thesis, The Johns Hopkins University, 1990); and Alison Murray, Robert E. Green, Marion F. Mecklenburg, and C. M. Fortunko, "NDE Applied to the Conservation of Wooden Panel Paintings," *Fourth International Symposium on Nondestructive Characterization of Materials in Annapolis, Maryland, June 11-14, 1990* (New York, 1991 [in press]).

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ART IN TRANSIT
Studies in the Transport of Paintings

Edited by
Marion F. Mecklenburg

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