AIR-COUPLED ULTRASONIC SYSTEM FOR DETECTING DELAMINATIONS AND CRACKS IN PAINTINGS ON WOODEN PANELS

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ABSTRACT

It has been established that the risk of damage to paintings on wood ("panel paintings") increases with the presence of cracks, delaminations, and their associated stress concentrations. Such flaws can originate and increase in size as a result of fluctuations in temperature and relative humidity, as well as shock and vibration. Many internal flaws cannot be detected either visually or by traditional testing techniques, and it is difficult, therefore, to assess the risk transportation poses to panel paintings.

Air-coupled ultrasound has been used to assess the condition of two panel paintings (*Parental Admonition* [a copy of the original] and *Women Gathering Yucca Plants*), in a non-contact, non-intrusive manner; this method provides information complementary to that given by radiography. It has been demonstrated that the ultrasonic system is clearly more suitable for detecting specific types of flaw, such as in-plane cracks and delaminations. The system enables measurements to be easily made of highly anisotropic and inhomogeneous materials such as wood.

The ultrasonic system used in this study has a superior signal-to noise ratio because it uses efficient transducers, low noise pre-amplifiers, and a phase-sensitive superheterodyne ultrasonic system that has analog signal averaging and filtering components. The signal can be exploited to yield both amplitude and phase information. The ultrasonic system also incorporates a mechanical scanner to produce easily interpreted two-dimensional images of large areas of paintings to give a clear indication of their condition. The results can be further enhanced by using image processing techniques.

INTRODUCTION AND BACKGROUND

Wood has often been used for a support for paintings. The structure of a typical panel painting may include the following layers: the wooden support (often oak or poplar); the

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ground or gesso layer (gesso is rabbit skin glue and calcium carbonate or calcium sulfate), which sometimes includes linen; the underdrawing; the paint layer; the varnish; and any retouchings. Later artists used both solid wood and wood products such as hardboard for supports, with surface layers that include gesso, gesso and linen, and paper. Throughout the centuries, some works of art and furniture, such as marquetry pieces, have a top surface of veneer (a thin layer of wood).

Catastrophic failure is much more likely in panels with severe stress concentrations caused by cracks and delaminations. For this reason it is imperative to detect, locate, and treat these flaws. By maintaining constant relative humidity, the lifetime of these artifacts can be prolonged; however, this high-maintenance environment cannot be achieved in all circumstances, for example during the transportation of works of art. If flaws can be detected, repairs can be made and predictive computer models (using finite element analysis) can anticipate the conditions that could lead to failure of the object. These conditions, including temperature and relative humidity changes and certain shock and vibration impacts, can then be avoided. It is possible to use computer models to predict the stresses in the individual components and in the entire painting, once any flaws have been detected.[1]

Detecting flaws in panels is not a trivial technical problem because wood is a highly anisotropic and inhomogeneous material and because conventional techniques cannot always locate cracks and delaminations. Moreover, working with art objects imposes restrictions that are not necessary when testing industrial materials. For example, contact ultrasonic methods should be avoided because they require pressure to transmit and receive the ultrasonic signals.

Air-Coupled Ultrasound

Much has been written about nondestructive testing methods used to examine paintings.[2] Flaws such as delaminations and cracks at certain angles have not been detected with traditional techniques such as radiography because the density change at these flaws is too small to be seen. The ultrasound technique is very useful in detecting delaminations and cracks oriented perpendicular to the sound beam because the signal is stopped by any delaminations and the amplitude is registered as zero. When a crack is at an angle, both ultrasonic and radiographic techniques can be used to advantage.

Air-coupled ultrasound uses air as a couplant, which does not saturate the material being examined, change its properties, or leave residues and therefore brings no danger of damage or contamination as other couplants do. This is true as long as the power or amplitude of the sound-wave is not too great.

The background and previous air-coupled ultrasound work has been discussed before.[3] The low signal-to-noise which is one of the major limitations of the air-coupled ultrasound technique, can now be overcome through the judicious selection of the critical components, including transducers, transmitting and receiving electronics, and the use of appropriate signal processing methods. Because of transducer limitations, operation is not possible in the pulse-echo mode, where only one transducer is used to send and receive the signal; this means that both sides of the painting or sample need to be accessible.

Materials with low acoustic impedances are more easily examined with air-coupled ultrasound because the acoustic impedance mismatch with air is low. Examples of materials that can be examined include: ligneous materials, foams, fibre-reinforced composites, rubber, paper, and non-metallic composites. Using non-contact ultrasound, the wood industry has made distance measurements and has located cracks and holes in wood, decay in lumber, and blows (delaminations) within hardboard, insulation board, and particle board.[4] Air-coupled ultrasound would be extremely advantageous in this field because of the coupling difficulties between the transducer and wood.[5]

The present work differs from past ultrasonic work on art objects, which used contact techniques with gels or pressure to examine stone, metal, and waterlogged wood, making measurements at specific points rather than over complete areas.[6] The technique used here allows entire paintings to be examined and comparisons to be very easily made between local and adjacent points, thus enabling contextual information to be obtained. This paper is the culmination of research in which air-coupled ultrasound has successfully examined samples used to mimic panel paintings. The samples were made with different flaws (delaminations and cracks), supports (oak, poplar, and hardboard), and surfaces (paint, gesso, gesso and linen, paper, and veneer); each sample varied one of these parameters at a time.

EXPERIMENTAL SET-UP

The main component of the air-coupled ultrasound system in this work was the phase-sensitive superheterodyne measurement system that generated and processed the ultrasonic signals.[7] It was linked to a commercial C-scan system which controlled the position of the two transducers on either side of the painting in the XY-plane. During the experiment, computer programs controlled the ultrasonic measurement and scanning systems. They also stored the data for the amplitude, phase, x and y positions, and the measurement system settings.

The system operated between 50 kHz and 5 MHz. The ultrasonic measurement system had modules that contained different components including: an IF oscillator and quadrature phase-sensitive detectors; a direct digital synthesizer; a high power gated RF amplifier; a broadband RF receiver; a mixer and IF amplifier; gated analog integrators; a coherent timer; and a 12-bit analog to digital converter (A/D converter).

The piezoelectric transducers used operated at 0.5 MHz and were spherically focused at around 5.08 cm (2.0 inches). During the experiments, the generating transducer was brought very close to the back surface of the sample, and was therefore focused within the wooden panel. The receiving transducer was focused on the sample-air interface of the front surface. This configuration ensured that the maximum energy entered the painting, to obtain the best resolution possible while maintaining the safety of the painting.

SAMPLES

The first painting examined came from the private collection of Dr. Hans Goedicke of Baltimore, Maryland. The painting, *Parental Admonition*, also known as *The Brothel Scene*, was a studiopiece (a copy from the same studio as the original). The original was painted by Gerard Terborch around 1654-55. The panel was oak and had a thickness of 3.6 mm (0.14 inches). Photographs of the front and back of the painting are shown in Figures 1a and 1b. The painting was of interest because of cracks in the wooden support, the craquelure or cracks in the paint layer, and because the painting had been "cradled". Cradling is an intrusive conservation treatment, used from the late 18th century until the early 20th century, where a secondary wooden support was added to constrain the panel dimensionally.

The second painting, *Women Gathering Yucca Plants*, is owned by the National Museum of American Art, the Smithsonian Institution (accession number 1969.64.9). It

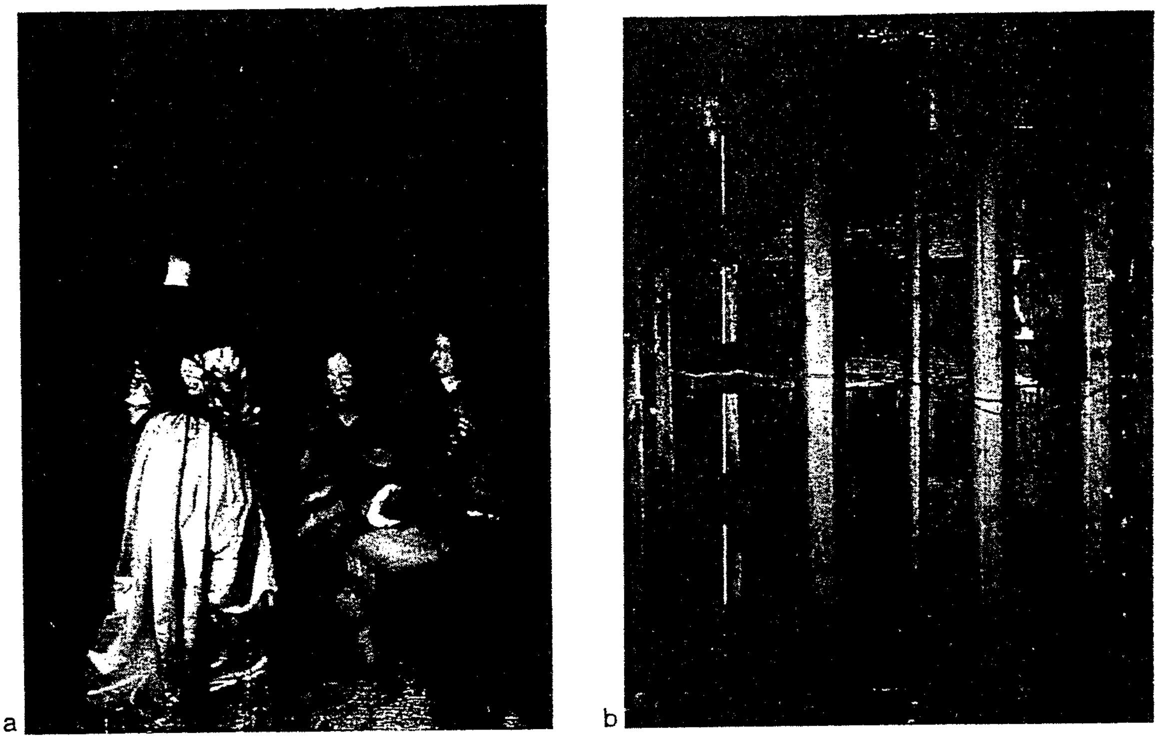

Figure 1. (a) Photograph of the painting *Parental Admonition*, (b) verso

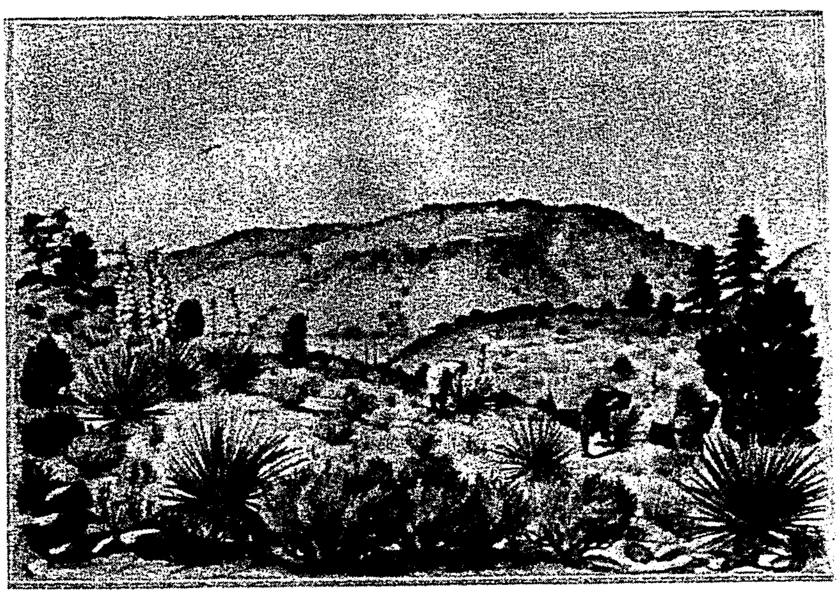

Figure 2. Photograph of the painting *Women Gathering Yucca Plants*, National Museum of American Art, Smithsonian Institution, transfer from the U.S. Department of the Interior

was painted by an unidentified artist in the 20th century and is shown in Figure 2. It is a watercolour and ink painting on illustration board (laminated paper board with paper layers glued to its surface) mounted on hardboard. The painting was approximately 6 mm (0.24 inches) thick. The illustration board had delaminated from the hardboard in certain, hard-to determine areas.

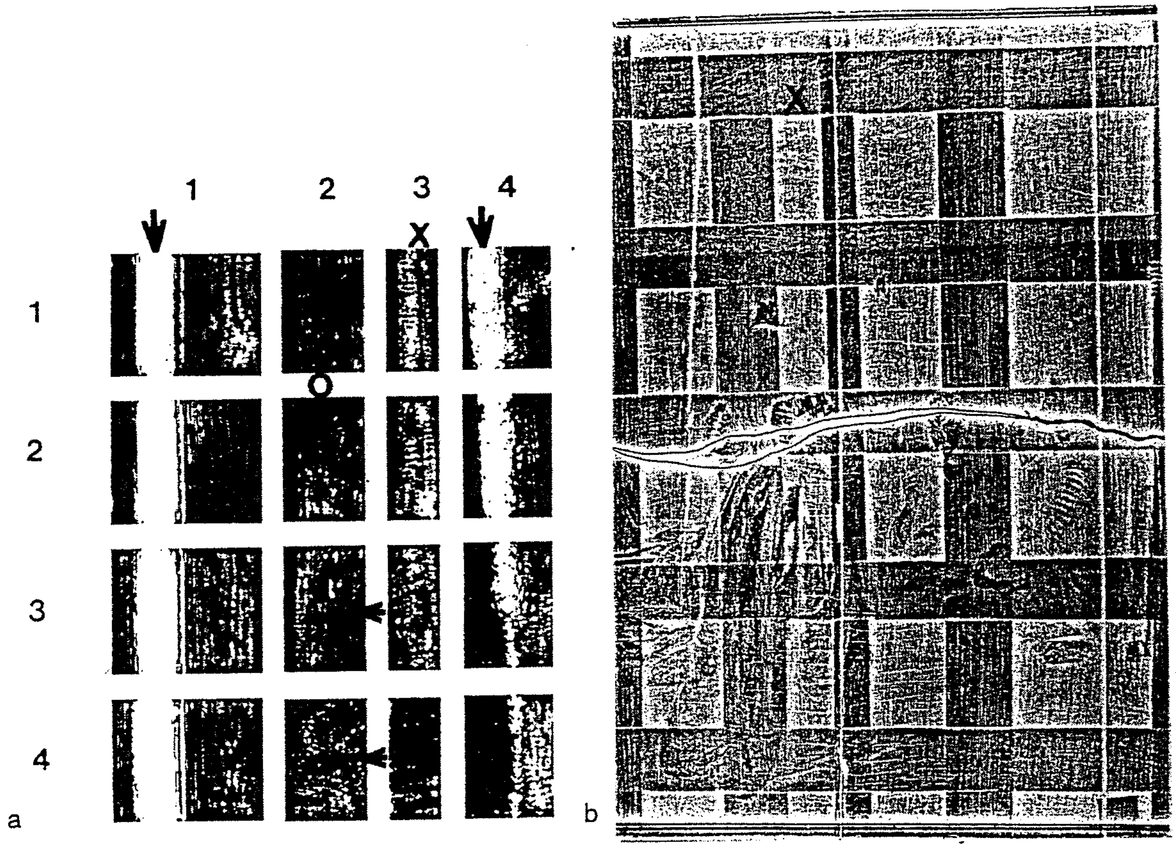

Figure 3. (a) Amplitude results from ultrasound scan of painting *Parental Admonition*, (b) xeroradiograph of the painting *Parental Admonition*: X is near closed crack which is hardly visible, and other features seen are the open cracks, the cradle, the hanging wire, and the image from the paint layer (x-ray tube was 130 cm or 51.2 inches above film, settings were between 40 and 60kV, 5 mA, and exposure time was one minute)

RESULTS

The results of air-coupled ultrasound investigations are shown using two-dimensional representations known as C-scans. Four ultrasonic parameters possible are: amplitude, phase, "processed" amplitude, and "processed" phase, where "processed" refers to the image processing technique of thresholding, where all the pixels above a certain grey level are shown as black and the pixels below the level are white. The first two types of amplitude scans will be shown in this paper. In the unprocessed amplitude images, the light areas indicate regions where the ultrasonic signal was easily able to penetrate the sample and the darker areas show where the signal was not been able to penetrate. Gradations of this can be seen in the unprocessed amplitude scan with the different grey levels. In the processed amplitude images, the light areas show regions where ultrasound has not been able to penetrate through.

Parental Admonition

Investigations were made of the cradled painting *Parental Admonition*. In this case, the cradle on the painting had not adhered well to the panel so that the signal-to-noise ratio was insufficient to allow an investigation of the entire painting. Thus ultrasonic scans could be performed only in the 16 areas between the battens of the cradle. A variety of artifacts can be seen in the ultrasonic C-scan of the amplitude results shown in Figure 3a.

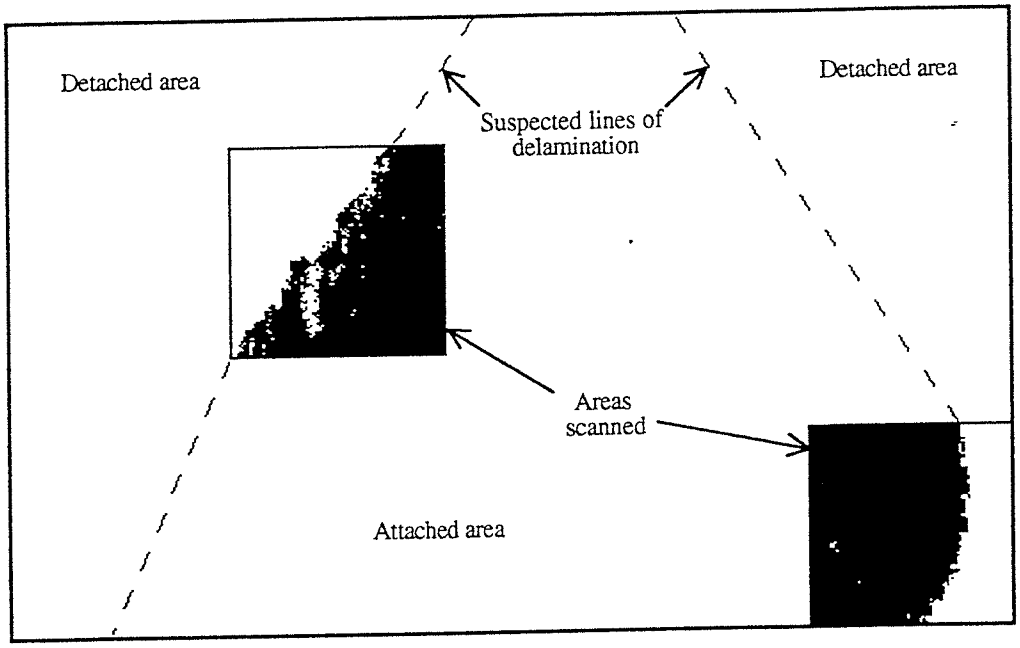

Figure 4. Outline of the front of the painting *Women Gathering Yucca Plants*, showing processed amplitude ultrasonic results from scanned areas (dotted lines show places at which it is suspected that the paperboard has become delaminated)

Two types of cracks exist: open cracks, where there is a visible opening to the other side, and closed cracks, where this is not the case. The open cracks appear as white lines (indicated by large arrows) and are larger on the ultrasonic image because of diffraction effects. Open cracks may mask other nearby artifacts, such as other cracks or paint craquelure. The closed cracks are dark lines (one is indicated by an "X").

Many of the vertical lines correspond to grain and closed cracks in the wood. Using the ultrasonic data only, it is difficult to distinguish the lines due to grain and those due to cracks. For example, in the two areas located in the second column and first and second rows, the lines could be indicative of either grain or cracks (adjacent to the circle).

The horizontal lines in the two areas in columns two and three and rows three and four are the craquelure running perpendicular to the grain. Some of the craquelure is identified by small arrows. Knots can also be seen in the first column, first row.

The closed crack marked by the X is detected with the ultrasound, but could not be detected visually or by xeroradiography (Figure 3b). In the positive xeroradiograph, the high density areas appear dark and those of low density appeared light. Visually it is very difficult to determine if the line indicates a crack running all the way through the panel, or merely an indentation in the wood.

Women Gathering Yucca Plants

Figure 4 shows the outline of the painting *Women Gathering Yucca Plants* (Figure 2), and the results from ultrasonic imaging of two areas within the painting. The processed amplitude scans are used as they show the delaminations most clearly.

The regions where the paperboard is detached from the hardboard are white. The dotted lines show the places at which it is suspected that the paperboard has become delaminated. The entire painting would need to be scanned to validate these lines. As expected, the xeroradiography (which is not shown) does not detect any delaminations.

IMPORTANCE AND FUTURE DIRECTIONS FOR ART CONSERVATION

Previous work has shown that air-coupled ultrasound can detect cracks and delaminations in panel paintings. The ultrasound can penetrate typical thicknesses of panel paintings, the thickest oak panel being 1.6 cm (0.63 inches), the thickest poplar panel being 2.0 cm (0.79 inches), and the thickest hardboard panel being 0.6 cm (0.24 inches). Thicker panels of all materials could probably be examined with additional signal processing such as time signal averaging.

The different ultrasonic results (amplitude, processed amplitude, phase, and processed phase) can be used to advantage to display certain types of flaws more clearly. Delaminations are most effectively shown with the processed amplitude scans, even when the paint layer has uneven thicknesses, while the amplitude scans show the degree of delamination. The amplitude scans better define cracks in radially cut panels, while the phase scans isolate them better in the tangentially cut panels. It is therefore useful to take both amplitude and phase measurements.[8]

Air-coupled ultrasound could also be used to examine paintings on canvas as the ultrasound easily penetrates paint, linen, and gesso layers. Flaws similar to those detected in panel paintings, such as delaminations between layers, could be found. Furniture pieces could also be investigated. It is conceivable that three-dimensional objects could be examined, although the results would be more complex and would need more interpretation.

As well as detecting delaminations and certain cracks, air-coupled ultrasound has other advantages over radiographic techniques. X-ray radiography and xeroradiography sometimes show the paint layer which may obscure other information found in a radiographic image. Also radiographic techniques cannot be used to examine a support with a lead white paint layer as x-rays aren't able to penetrate it, and therefore any information about the painting is masked. Image-processed ultrasonic amplitude scans, however, are not affected by changing paint layer thicknesses and ultrasound can penetrate the lead white paint layer.

The unique features of this system that make it of value in the conservation field should be emphasized. Ultrasonic components, such as the transducers, do not touch the material being examined. There is no evidence that the ultrasonic wave causes any damage. Moreover, a portable version of the system could be designed quite cheaply; for example, it could use less expensive transducers and a simpler transducer holder than were used in the experiments described here.

CONCLUSIONS AND FUTURE WORK

An air-coupled ultrasonic imaging system has been assembled for inspecting wooden panels. This system operates in the through-transmission mode, using two transducers, one on either side of the object; one transducer sends an ultrasonic signal and the other receives it. The signal has sufficient signal-to-noise and can be exploited to yield both phase and amplitude information, as well processed amplitude and phase versions using the image processing technique of thresholding where all the pixels above a certain grey level are black and the pixels below that level are white. Two-dimensional scans of samples are generated.

The ultrasound system reliably detected flaws in the panel paintings *Parental Admonition* and *Women Gathering Yucca Plants*. Cracks, delaminations, craquelure in the paint layer, wood grain, and knots found within the samples were all clearly imaged by the system.

The system maps flaws in wooden panel paintings that cannot be detected by other techniques such as radiography. The ultrasonic system was clearly shown to be more suitable for detecting certain flaws, such as in-plane cracks and delaminations.

Further work is needed in the area of image recognition in order to improve the reliability and ease of use of the air-coupled ultrasound system. In particular, it is important to develop methods that will distinguish between images of natural anomalies (grain) and flaws (cracks). Incorporation of information from visual examination and from other nondestructive techniques, such as radiography, will be useful here. As new transducers become available, the same transducer will be able both to send and to receive signals; this will remove the need to access both sides of the art work. Using more image processing may also be useful.

Air-coupled ultrasound is a potentially important, non-intrusive inspection method. The technique can yield information that will improve the long-term care of paintings on wood and, by implication, other works of art.

Acknowledgements

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