their ability to plastically deform after developing a maximum stress. At -3° C, many of the acrylic paints exhibited drops in strength although their modulus continued to increase. This may indicate fracture sensitivity in acrylic paints at very low temperatures.

Desiccation effectively increases the temperature at which acrylic paints become brittle when cooled. At 50% RH, some acrylics were brittle at 5° C, but at 5% relative humidity many were brittle at temperatures as high as 11° C. Alkyd paints are also very brittle at low temperatures and low relative humidities.

The experiments presented here indicate that cold transport environments are potentially dangerous to acrylic and alkyd paint films because their ability to respond to force by deforming is diminished, thus making them susceptible to shattering. Aircraft holds, for instance, generally have a temperature of approximately 10° C, although some holds have temperatures as low as 5° C.[3] Acrylic paint in 5% RH is brittle at both of these temperatures, but if its environment were buffered to a higher relative humidity the chance of it breaking due to shock or vibration would be lessened.

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DETECTION OF DELAMINATIONS IN ART OBJECTS USING AIR-COUPLED ULTRASOUND°

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Abstract

The possibility of using air-coupled ultrasound to find delaminations between layers in paintings was investigated. Simulations of modern paintings were constructed with hardboard as the support layer, and a layer of gesso, an animal hide glue and chalk, as the upper layer. Delaminations were introduced between the two layers. Scanning the samples using air-coupled ultrasound clearly showed these flaws. A transmitting transducer, which was 25 mm in diameter and had a focal length of 51 mm, was placed 11 mm from the back surface of the sample and an identical receiving transducer was placed 51 mm from the front surface. The transducers were operated in a tone burst mode at a center frequency of 475 kHz. Signal enhancement techniques were used to improve the contrast of the data.

Introduction

The care of wooden art objects is rendered more difficult by the presence of cracks, voids, and delaminations. Computer analysis shows that cracks in wood promote severe stress concentrations that are aggravated by environmental and other stresses.[1] Unfortunately, many of these internal anomalies are not easily visible, making assessment of the various risks to art works difficult. In the case of a panel painting, its structural condition can be mapped using nondestructive testing techniques, in order to predict how it will respond mechanically over time in different environments. It can then be decided whether the object can be safely shipped to special exhibitions, and what plans can be made for proper display, storage, and conservation.

Various nondestructive methods for detecting voids, hidden cracks, and fine fractures in paintings have been investigated.[2] These methods have been incorporated into the repertoire of techniques from which conservators draw, to prevent the premature failure of objects.

Investigations of wooden panels and paintings have shown that xeroradiography has the advantage over x-ray radiography as xeroradiography's edge enhancement property enables flaws to be displayed prominently. It also uses equipment compatible with that typically found in conservation laboratories.

Research has shown that air-coupled ultrasound, a non-contact, nondestructive testing technique, can detect delaminations and cracks at certain angles that radiography cannot. Unlike radiographic techniques, ultrasound is not a health hazard for the user. The need for a non-contact ultrasonic method for use in the art conservation field has been discussed before.[3]

In working with ultrasound, industry has been able make use of traditional couplants, such as water, oil, and grease. Air coupling is a non-contact technique which may be faster and safer for examining museum objects. Air was not considered until recently because of the low signal-to-noise ratio caused by the high acoustic mismatch between solid materials and air. Air-coupled ultrasound has now matured into a viable method as the transducers and support electronics needed to overcome the signal-to-noise problem have become available.

There is a considerable body of literature on the subject of air-coupled ultrasound.[4-12] Historically, the main obstacle to the use of air-coupled transducers was the misconception that the attenuation in air is very high. In fact, it is only 20 dB/m at 600 kHz and 20°C. There is still, however, a substantial signal strength loss between the test material and the air, as the acoustic impedance of the material is five orders of magnitude larger. This is one of the major limitations of the air-coupled ultrasound technique. This limitation can now be overcome through the judicious selection of the critical components, including transducers, transmitting and receiving electronics, and appropriate signal processing methods.

The use of ultrasound in art conservation is not a new idea. Conservation scientists have performed ultrasonic tests on a variety of materials. For instance, ancient masonry buildings have been tested before and after repairs to determine the penetration and diffusion of grout, and to measure the degree of strengthening effected in masonries through repair.[13] In this work, correlations were found between the sound transmission data, aging tests, changes in the mechanical properties, and flaws.

The calcerous stone monument "St. George and the Dragon" was examined with ultrasound by Yakhont and Pimenov to determine the lithogical composition and other characteristics of the stone, as well as the existing damage.[14] The possibility of using ultrasound to test metal castings in order to show their condition and thickness has been discussed.[15] Measurements taken on wetted archaeological woods have shown the homogenization and strength of waterlogged wood.[16] Ultrasound was also used in conjunction with thermography to investigate whether Leonardo da Vinci's lost painting "The Battle of Anghiari" could be present beneath six large murals by Georgio Vasari.[17,18]

Inspection Problem

The objective of this work was to investigate whether air-coupled ultrasound was a feasible technique for finding delaminations in modern art paintings, between the support layer (hardboard) and the gesso layer. Such delaminations might be caused by environmental stress, imposed, for example, by changes in relative humidity, which ultimately affect the mechanical properties of the different layers. Another possible reason may be that the layers had never adhered properly.

Air-coupled ultrasound systems suffer from low signal to noise performance, which limits the flexibility of their use. For example, operation in the pulse-echo mode, where one transducer is used to send and receive the signal, can measure distances, but cannot perform analyses of subsurface features.

The safety of the object during examination is of utmost importance. Positioning the transmitting transducer close and unfocussed on the back surface of the panel, reduced the sound pressure and minimized the likelihood of damaging the object.

Experimental Configuration

The experimental set-up was reported in a previous paper.[20] One transducer sent the signal through the sample and another received the signal after it had travelled through the sample (Figure 1). Both transducers were 25 mm in diameter, had focal lengths of 51 mm, and had frequencies of 475 kHz. The transmitting sample was only 11 mm from the back surface of the hardboard panel, while the receiving transducer was 51 mm away from the gesso surface.

The transducers were held in a "U-shaped" yolk attached to a frame which could move along one axis (Figure 2). The apparatus was mechanized so that line-scans could be made of the samples. The stepping distance of the apparatus was 0.5 mm. In future work, the air-coupled ultrasonic system will be combined with c-scanning capabilities so that two dimensional images can be made. The stepping resolution will also be improved.

The resolution of the system was determined by scanning the signal from a small transducer (a "pinducer" of radius 0.8 mm) with a typical air-coupled transducer. At the focal distance, the receiving area is 3.2 mm in diameter. The actual resolution was calculated to be 1.6 mm, by subtracting two times the radius of the pinducer from the measured focal diameter. This is in excellent agreement with the theoretically predicted value (using the Rayleigh criterion) of 1.6 mm.

Other factors are important to consider when discussing the resolution of the system. The speed of sound in air is substantially lower than that in the hardboard. This means that the wavelength in air is shorter than that in hardboard. This mismatch caused severe refraction of the sound transmitted through the air-hardboard interface (Figure 3). The transducers are, therefore, not able to focus inside samples to find interior flaws.

Simulated panel paintings with anomalies were made by the Canadian Conservation Institute. Four panels of hardboard, 200 mm x 200 mm x 6 mm, were tested:

1. blank hardboard panel,
2. panel sanded overall to ensure good adhesion and to which a uniform layer of rabbit skin glue gesso of thickness of 0.6 mm,
3. same as panel 2 except that areas of failure were simulated by inserting thin sheets of plastic; the remaining surface was sanded to ensure good adhesion.
4. same as panel 2 except areas were left unsanded to promote adhesion failure and delamination.

The use of plastic sheet inserts (generic polyester) to simulate delaminations was developed by the aerospace industry. The method has been used on laminated composite panels both in industry and in art conservation.[21]

Panels 3 and 4 were also x-ray radiographed and xeroradiographed.

Results

The ultrasonic signal was able to traverse each panel. The experimental results from panel 3 are shown in Figure 4. The inset diagram shows where the line scan was made, and the main graph shows the amplitude of the received through-transmission signal as a function of position.

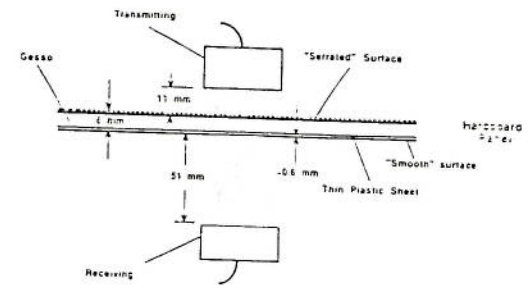

Figure 1 Experimental Configuration

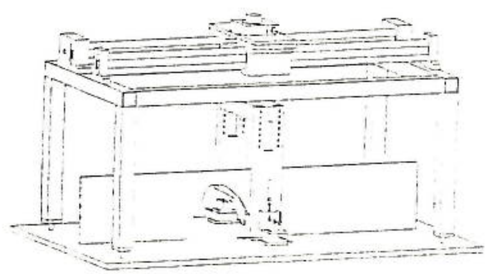

Figure 2 Fixture for Air-Coupled Ultrasonic Technique

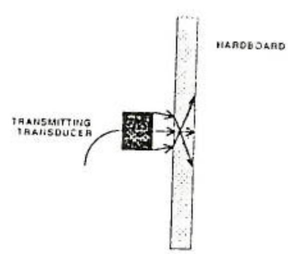

Figure 3 Ray Bending of Transmitted Sound

Two signal enhancement techniques were used to transform the ultrasonic data. "Running signal averaging" was used to obtain the mean value of five adjacent points which was used to remove rapid amplitude variations of the signal (dotted line in Figure 4). A simple transformation was then used to improve the contrast of the signal,

$$A = ((1-\langle T\rangle^2_X)/\langle T\rangle^2_{UNFLAWED})^{1/2}$$

where $\langle T\rangle_X$ is the running average of N adjacent amplitude points (N=5), and $\langle T\rangle_{UNFLAWED}$ is the average transmitted amplitude from the unflawed sample, panel 2, using all the data points. The enhanced ultrasound data from the hardboard panels 3 and 4 are shown in Figures 5 and 6. The results show the flawed regions in the panel with plastic inserts. The inserts were also visible with the radiographic techniques, although this was due to the increase in density from the inserts rather than from delaminations. Neither the ultrasound nor the radiographic techniques detected any delaminations from panel 4, where areas had been left unroughened to promote de-adhesion.

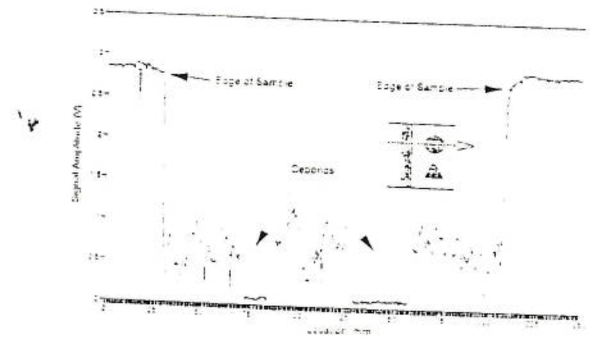

Figure 4 Ultrasonic Results for Line Scan of Panel 3

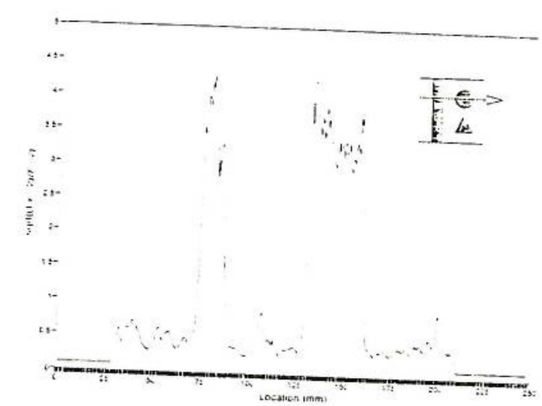

Figure 5 Ultrasonic Results for Line Scan of Panel 3 After Enhancement Techniques (the flawed areas contained plastic inserts, resulting in high contrast)

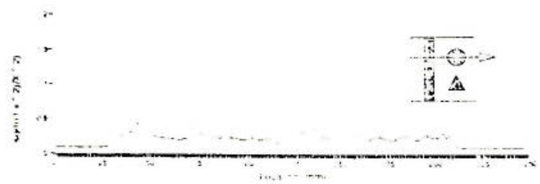

Figure 6 Ultrasonic Results for Line Scan of Panel 4 After Enhancement Techniques (the flawed areas were left unroughened, resulting in low contrast)

Conclusions

Simulated delaminations have been reliably detected using air-coupled ultrasound. The areas of internal anomalies were enhanced using signal averaging and a transformation. It can be concluded that the air-coupled ultrasound technique shows great promise for the art conservation of panel paintings. Future work will include detection of delaminations on actual paintings.

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Preface

This symposium, Materials Issues in Art and Archaeology, is the third in a series in which the goal is to present recent work on (1) ancient materials, (2) the technologies of selection, production and usage by which they are transformed into the objects and artifacts we find today, (3) the science underlying their deterioration, preservation and conservation, and hopefully, although this goal is achieved infrequently, (4) socio-cultural interpretation based on an empirical methodology of observation and measurement.

Our call for papers read: "This symposium will provide a multidisciplinary forum for reporting and interpreting new developments in technical studies of material culture and in the conservation science required to preserve that heritage. In order to promote a dialogue among empiricists who examine the materials science and cognitive and cultural behavior underlying art, archaeology and technology, those who develop the materials science and technology underlying modern artifacts, and those who attempt to elucidate the underlying mechanisms of deterioration and means of stabilization, we solicit contributions in the following areas:

THE ROLE OF TECHNOLOGY IN MATERIAL CULTURE:

Processing evidence from workshops and industrial debris.
Bone, ivory and stone technologies.
Lead-based processes, arsenical copper, wootz.
Innovation and technology transfer vs. conservativism and craft tradition in ceramics.
Analysis of properties to interpret function.
Cultural, historical and technological reconstruction through artifact analysis.

CONSERVATION SCIENCE:

Mechanisms of deterioration.
Assessment and monitoring of condition.
Evaluation of methods of cleaning and consolidation.
Model tests of accelerated aging procedures.

CHARACTERIZATION THROUGH COMPOSITIONAL AND STRUCTURAL ANALYSIS:

New methods and applications including case studies using surface and/or bulk analysis, isotope analysis, nondestructive evaluation or techniques applicable in archaeological fieldwork.
Comparison of empirical data with textual or ethnographic accounts.

MECHANICAL AND PHYSICAL PROPERTIES OF MATERIALS AND/OR ARTIFACTS:

Optical properties and visual appearance.
Strength, wear and fracture.
Interfacial phenomena in composites, especially treated objects.
Replication studies.

Papers should report completed case studies and new applications, rather than potentially useful methods or work in progress. Our intent is to promote research in ancient technology, archaeology, art and conservation which shares the knowledge, methods and tools of materials science and engineering."