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Original article

Simulating mass loss of decaying waterlogged wood: A technique for studying ultrasound propagation velocity in waterlogged archaeological wood

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ABSTRACT

Often cultural conservators are asked to assess the preservation state of waterlogged wooden artefacts whose identity and rarity place an ethical barrier on the use of destructive analysis techniques. In addition, conservators are continually being challenged to find new ways of assessing the preservation of the underwater heritage, such as wooden shipwrecks, whilst in situ, and thus assist the process of managing such sensitive archaeological sites. Ultrasound compressional (p-) wave velocity has been researched in the past as a potential tool for estimating the preservation state of wooden artefacts and timbers. Its non-invasive principal complies with conservators' working ethics, while it has shown the potential of mapping and imaging submerged wooden archaeological heritage objects, as well as estimating the in situ preservation state. The aims of this paper are to present a viable non-destructive assessment method for cultural conservators for working on laboratory samples of waterlogged wood and to provide data for the analysis of in situ sites. This paper outlines the approach for the preparation of samples; the generation of controlled test-pieces for systematically quantitatively assessing the relationship between mass loss expressed as basic density and p-wave measurements; acoustic measurement; and the initial empirical results. Mass loss is achieved in a controlled and reproducible way for testing with ultrasound. The process incorporates a set of increasing wood degradation levels by gradually removing wood mass from waterlogged oak and pine test-pieces via drilling holes along the grain (longitudinal wood growth axis). This is followed by a chemical treatment with alkaline of the fully drilled wood test-pieces. The same test-pieces are used from zero to maximum degradation. This allows consistent observations, restricts variability and enhances interpretation of the results. The study considers wood both as a raw material and an artefact, here exemplified as the hull components of ancient wooden ships. Dimensions and cutting orientations of the test-pieces respect those noted in archaeological records. The focus is set on the RL and TL planes (radial and tangential axis respectively) and TL (tangential axis) planes, the main planes expected to be insonified with ultrasound considering timber conversion techniques in ancient shipbuilding. Ultrasound testing is performed within a reinforced polyethylene water tank, with the wood test-piece placed in between the transmitter and the receiver in good alignment. Using the trough-transmission immersion technique the time it takes a p-wave to travel through the test-piece together with the latter's thickness, are used to calculate the propagation velocity. Results demonstrate that ultrasound waves travel faster in the radial than in the tangential direction; although advancing the degradation, wood becomes more isotropic across the grain as indicated by the reduction of $V_{Radial}/V_{Tangential}$ ratio. Ultrasound velocity is unaffected by the structural differences between ring-porous oak and pine allowing quantitative results for a density range between 0.567 gcm^{-3} (fresh) and 0.292 gcm^{-3} (degraded) irrespective of wood species used. Two significant empirically derived equations can be used by the cultural conservator to derive a wood density level, a common bench mark for assessing archaeological wood degradation level.

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1. Introduction

Estimating the preservation state of archaeological waterlogged wood is vital for the archaeological conservator to design an appropriate treatment scheme. To date a number of destructive or near non-destructive techniques are assisting conservators in this procedure. Yet, minimum intervention is a fundamental conservation principle because intervention can limit the research potential of archaeological artefacts. Non-destructive tools which will move the science in this direction are imperative both in the conservator's laboratory, especially considering condition assessment of delicate and small artefacts, but also at larger scales such as wooden hulls in the field. Ultrasound's non-destructive nature is an obvious approach as it complies with conservators' working ethics [1], and specifically for studying wooden cultural heritage objects (WCHOs) [2], together with international rules and guidance for proper archaeological practice in situ [3]. Recently published overviews of commonly applied non-destructive methods suitable for studying WCHOs exist in the literature [4,5], but these currently lack reference to waterlogged archaeological material. This work aims to plug this gap and provide a practical approach for the use of ultrasonic assessment of such material.

2. Basic principles of p-wave velocity and ultrasound techniques

Ultrasound is a common diagnostic non-destructive tool from the forestry and forest products industry for assessing standing tress and grading timber [6]. It is based on the principal that changes in wood's density result in changes in the compressional (p-wave) velocity of ultrasonic waves propagated through a timber. Consequently, accurately recording p-wave velocity will provide a non-destructive measure of the wood's density. Measuring the archaeological wood's basic density (oven-dry weight waterlogged wood volume basis) and comparing it with the average basic density of fresh wood from the same species, is a standard method used by conservators to classify the degradation state of archaeological wood using the Residual Basic Density (RBD%) [7]. Knowledge of wood's remaining density assists the conservator to design conservation schemes and select appropriate conservation treatments and materials.

Ultrasound compressional waves (p-waves) are waves where particles are displaced parallel to the direction of motion of the wave. They are produced by piezoelectric transducers which convert the electrical energy to mechanical vibration and convert the returning echoes back to electrical signal. Piezoelectric ultrasonic transducers for wood inspection are available at frequencies ranging from 20 kHz up to a few megahertz [8], with a range of between 20 and 200 kHz being typical for whole tree field measurements but extending up to frequencies of 1–3 MHz for laboratorial use and experiments where wood samples tend to be smaller [9]. Ultrasonic inspection can be executed using either the through transmission or the pulse echo technique, of which through transmission is regarded as the most appropriate for lumber grading [10] and easiest to operate for measuring the velocity of propagation of the ultrasonic wave [9]. Also called direct transmission method, it utilises two transducers in line, the transmitter and the receiver, either in direct contact or not with the face of the sample under test, but always using a coupling medium (e.g. water) to provide no loss/scattering of the signal's energy between the transducers and the wood. The pulse echo technique, by comparison, utilizes one transducer which contains both the signal's transmitter and receiver and is useful for imaging the structure of a wood sample.

Ultrasound in archaeology has been tested in the past on a small scale as a non-destructive tool for evaluating the preservation state of waterlogged archaeological wood with the through transmission [11,12] and the pulse echo technique [13]. Recent studies using through transmission technique [14,15] have assessed waterlogged archaeological wood but after drying the wood to a moisture content of 8 or 12%, that is less than the Fiber Saturation Point (FSP) (average about 30%), or the point when free water enters the cell lumina and cavities and wood is classed as waterlogged. Maximum possible moisture content can be estimated based on the species' basic specific gravity (Gb) with typical values between 44 and 267%, but is rarely attained in living trees [16]; under laboratory conditions lightweight balsa wood can reach an MCmax over 900% [17].

Conservators typically classify waterlogged archaeological wood as deteriorated when its moisture content is above 150%, depending on the species, and always in line with signs of weak structure because of chronic deterioration [18]. Archaeological wood is highly deteriorated when its moisture content is above 400% [19] and RBD less than 40% [7]; water contents of more than 1000% and RBD about 20% have been recorded [20–22]. In fresh wood physical and mechanical properties such as propagation-wave velocity and modulus of elasticity, do not change over the FSP as a function of moisture content [16], but it is expected that since the water is not strongly attached to the wood cells, when sound propagates through waterlogged wood, acoustic losses take place, as free water molecules vibrate separately to the wood cells. Or else, there can be a mismatch with each of the components (wood and free water) resonant frequencies, which results in the reduction of the propagation velocity [23,24]. For this reason the presence of water is essential for the study of waterlogged archaeological wood.

The most systematic approach has been taken by Arnott et al. [25], who investigated the changes in ultrasound propagation properties with changing preservation state. They used two approaches to producing degraded samples; exposure of fresh wood to shipworm by deploying wood test-pieces in the sea for different lengths of time (up to 12 months); and secondly exposure of wood test-pieces to brown rot fungi in the laboratory. Ultrasound properties were tested on oak and pine discoidal test-pieces 15 mm thick grouped per principal wood growth axis (longitudinal, radial and tangential) inside a water bath at a centred frequency of 1 MHz using compressional waves with the through transmission technique [12]. Their results showed a general tendency of ultrasound p-wave velocity reductions for all wood growth axes with increasing wood degradation, as expressed by the basic density. However, the study experienced large data variability in the velocity measurements which could not be purely ascribed to wood degradation. The choice to work with bio-deteriorated fresh material caused a loss of control over experimental variables and test-pieces to work with because of the uncontrolled severity of degradation, and so the experimental reproducibility of the same degradation conditions was difficult to achieve. In these experiments the sampling strategy in relation to the punctuated speed of degradation (which related directly to the optimal spawning environmental conditions and the life circle of the shipworm), and to adverse weather conditions, resulted in measurements having to be taken in uneven steps and so it was therefore difficult to capture systematic step changes through the full degraded density range. These initial results have been applied in the field demonstrating the benefit to in situ interpretations [26].

3. Research aims

This study aims to produce a reliable, and reproducible, ultrasound through transmission immersion technique and establish a fundamental empirical relationship between wood density and