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NON-DESTRUCTIVE TECHNIQUES FOR DETECTING DECAY IN STANDING TREES

*Djamel Ouis**

Summary

This paper reviews the different techniques used to investigate whether the trunk of a standing tree is hosting rot or not. The most widespread and efficient techniques may in general be classified under two wide classes depending on the signal used for investigating the tree trunk. The first category includes the vibro-acoustical techniques using either vibrations at frequencies within the acoustical bandwidth or sound waves at acoustical or ultrasonic frequencies. The second class of techniques uses various methods based on electromagnetic radiation. There are furthermore some other techniques which are more or less destructive, and which are also presented in the current work. These techniques are destructive, but to a lesser extend than the well known fully destructive ones inasmuch as only a small sample is extracted from the tree trunk to be submitted to test.

Keywords: acoustic tests • decay detection • Densitomat • electromagnetic radiation • Fractometer • non-destructive testing • Pilodyn • Shigometer • ultrasound • vibration monitoring

Introduction

Wood has played a major role in the history of human beings to the extent that people have never thought of abandoning its use and its for this reason that historians have never referred to the 'wood age' in the life of humanity. Upon leaving the cave, primitive people relied on wood as the first building material. In modern society wood still fulfils an important function and, by its very use, prompts research into the construction of wooden built houses. Three factors have contributed to these developments; the relative abundance of wood as a building material, health (wood has a less degrading effect on health compared to other building materials like concrete), and improved techniques in the reduction of fire hazards. The use of wood is not restricted to building

*School of Technology and Society, Malmö University, SE-205 06, Malmö, Sweden.
E-mail: djamel.ouis@ts.mah.se

construction; the manufacture of furniture is almost 100 per cent dependant on forest products. Wood pulp is one of the principal raw materials in the manufacture of paper products. The comparatively low price and ease of transport of wooden poles has made them an incomparable substitute for their concrete and metallic counterparts in the support of electrical and telephone cables. While these examples where wood is the provider of either a raw material or as a semi-finished product, it is evident that as a natural renewable material, wood represents an important element in a country's investment. Like any other material wood has its defects, two of which are malformations like knots, splits and cross grain as a result of natural adaptive development and defects caused by external agents which decay and degrade its strength. This review is concerned with detecting (or identifying) the latter as wood is sought primarily for its strength. In contrast, the other defects are readily detected and often contribute to a series of aesthetic features which are sought after in the design of household furniture.

The difficulties in investigating decay in standing trees

Sweden prides itself in having the largest forest area and of being the main exporter of forest products in Europe, making a multi-million dollar investment in this vital industry. For example, it is involved in the large scale manufacture of specialised equipment like forwarder harvesters. At this early stage, it is therefore important that the highest quality of raw material is chosen to ensure the most efficient production and marketing processes. However trees, when under stress, are liable to attack by numerous fungal decay organisms which weaken the strength of the tree trunks. For example, in southern Sweden it is estimated that 15 per cent of the tree population is lost from fungal decay, i.e. one tree in six. Furthermore, a tree with a decayed trunk is of no value for later conversion and therefore has to be cleared away from the forest, an operation which incurs an unnecessary charge in time and effort. Before felling a tree, a woodsman assesses the internal condition of a tree trunk by striking it with a hammer. From experience, the response to the blow can determine the presence of decay, hence the term 'sounding'. This simple practice is not reliable as the test can only reveal 'sound' or 'decayed' wood and no correlation can be established between the degree or stage of the decay and the response.

In order to determine the strength characteristics of the trunk of a living tree, a test method has to fulfil reliable and efficient criteria. The performance of the test must be fast, preferably by portable lightweight equipment, is not complicated in its application, is versatile and the price presents good value for money. There are a few instruments based on sonic and vibration principles, the use of which has been reviewed by OUIS (1996), for example *Metriguard's Stress Wave Timer*, the principle of which is based on measuring transit time made by a stress wave generated by hammer stroke across the tree trunk (BETHGE *et al.*, 1996) (Figure 1).

Although the technique of assessing the *through transmission time* is easy and rapid using relative cheap equipment, its main drawback is that appreciable time differences can only be registered in hollow or relatively wide tree trunks (SCHAD *et al.*, 1996). Another technique which has been used with broadleaved tree species consists of introducing a single frequency signal frequency signal to a tree trunk and to register the response. Where a is subject to decay, a more pronounced response was recorded (McCRACKEN and VANN, 1983). This technique presents potential applications, but has still to be applied to softwoods (conifers).

Methods based on ultrasonic techniques have also been tested on standing trees, but their introduction to determine the condition of

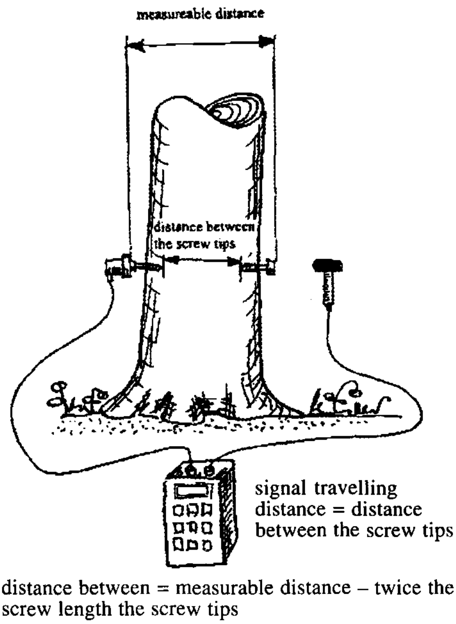


FIGURE 1. Description of the Stress Wave Timer technique. Top: principle (Bethge et al., 1996), and bottom: in practice (Mattheck and Bethge, 1992).

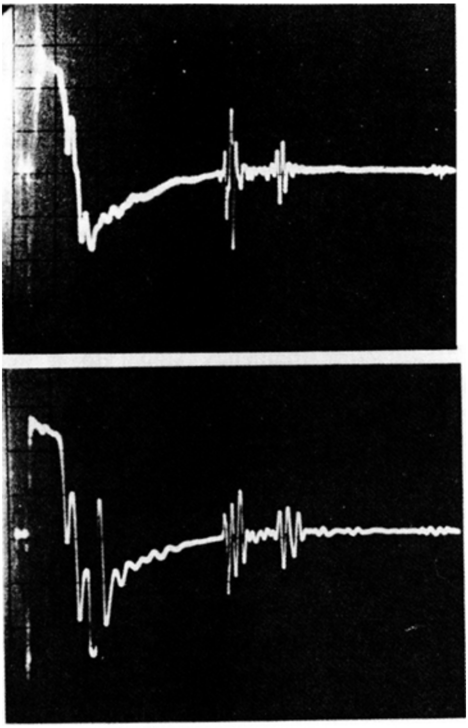


FIGURE 2. Echo trace from a tree trunk subject to hollow rot using ultrasonic pulse signals. Upper: signal at 1 MHz, lower: 0.5 MHz. From (Okyere and Cousin, 1980).

live wood only began in the late 1950s (WAIS and WOODMAN, 1957). Several attempts have been made to detect various kinds of defects in wood by the pulse echo method (MAKOW, 1969). A special application of this method has also been used to investigate flaws in tree trunks resulting from advanced decay deterioration, but reliable results could only be obtained from trees with excessive hollow trunks (OKYERE and COUSIN, 1980). The major difficulty encountered in the use of ultrasonics for the internal inspection of standing trees is the coupling material between the transducers and the bark of the tree which absorbs ultrasonic waves. (The bark is removed and replaced by an ultrasonic transducer.) There are several kinds of coupling materials but not all have been tested on trees and they require further trials in their use. The other difficulty in the use of ultra-sonic testing in wood is the attenuation of the signal. For a lower attenuation, the working frequency must be diminished, but for lower frequencies, the wavelength of the signal may get large enough not to differentiate the details of the decay (defect). It should be noted that there has been renewed interest in the ultrasonic detection of decay in wood (BAUER *et al.*, 1991; UPCHURCH *et al.*, 1992). On the other hand ultrasonic characterisation of wood has been focusing on the measurement of wave velocity (v) which diminishes for decayed wood. Wave velocity is given by:

$$v = \sqrt{\frac{E}{p}\,\mathrm{m/s.}} \qquad (1)$$

where E is the *modulus of elasticity*, MOE (in N/m^L), a measure of the strength of the material and p its density (in Kg/m^3) from which it can be seen that the decayed wood has a lower value of MOE than that of sound wood resulting in the reduction of the wave velocity. From earlier trials it has been found that the MOE value of decayed wood is reduced by half that of sound wood when its relative weight loss may be as small as one per cent (WILCOX, 1978). Incipient decay can sometimes only be detected by microscopic examination or visual assessment which can give rise to misleading identification. The use of ultra sound in the strength grading of timber is not new, with the earliest reference to such attempts dating back 40 years (WAIS and WOODMAN, 1957). The *ultrasonic pulse echo method* has been shown to be effective for large hollow areas in the trunk (OKYERE and COUSIN, 1980). Another ultrasonic method measures the energy of the wave at its passage through the material which diminishes appreciably with decayed wood. This technique has been used on a limited scale in a pilot study in Sweden (ANDERSSON and BJURULF, 1993) and together with the previously mentioned techniques their improvement is likely to provide potential options for its development. During the last decade there have been advances in various ultrasonic techniques which have greatly improved the non-destructive evaluation of defects in wood (KRAUTKRAMER and KRAUTKRAMER, 1990). During the last few years extensive research in ultrasonic testing of woody materials has been instigated in some countries of Europe with the aim of developing rapid and not too costly techniques for use in the woods (SANDOZ, 1994) or in the sawmill (HAN and BIRKELAND, 1992; SANDOZ, 1996).

FIGURE 3. Earlier use of X-ray diagnosis techniques for imaging the inner condition of the trunk of a street tree. From (Maloy and Wilsey, 1930).

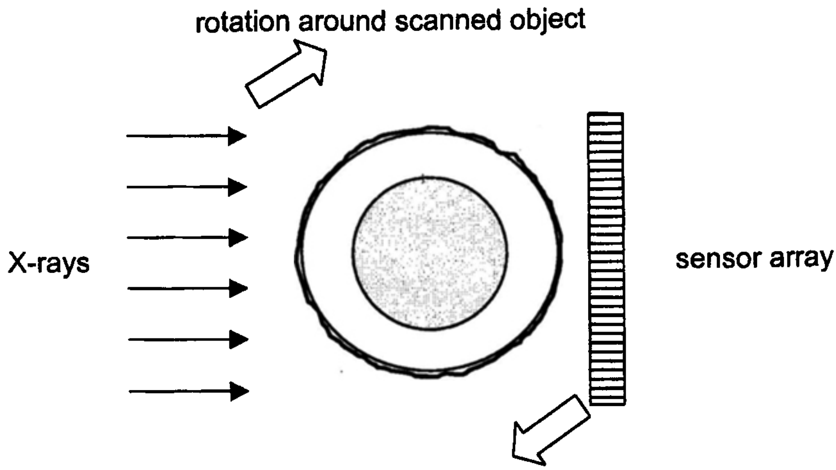


FIGURE 4. Schematic representation of a CT scanner. Several measurements are recorded with each pulse of the X-ray tube.

The use of a method off assessing the strength of standing trees still has to be developed. The non-destructive investigation of the state of standing trees has been the subject of research for many decades. Most, if not all the methods tried have been based on the imaging of the human body. The earliest use of X-rays of trees dates back to MALOY and WILSEY (1930) and resumed with the development of X-rays densometric measurements by COWN and PARKER (1978) and ESLYN (1959). A variant technique based on electro-magnetic radiation using *Ground Penetration Radar* (GPR) measures the degree of reflectivity of a short radar signal at the interface between two materials with different electrical and magnetic properties (which could be the sound and the decayed parts inside a tree trunk). Although GPR signals were developed for geophysical research, promising results were obtained when applied to trees by MILLER (1989) and SCHAD (1996). Another related technique using γ-radiation, consists of measuring the degree of attenuation of γ particles at their transmission through the material under examination. This type of examination has been successfully applied to wood in general and trees in particular by FILER (1972) and PARRISH (1961). Forest and arboricultural research has also been witnessed an extensive application of the *computer tomography* (CT) technique for the scanning and imaging of standing tree trunks (HABERMEHL, 1990; HABERMEHL and RIDDER, 1992; HABERMEHL and RIDDER, 1995; ONOE *et al.*, 1984 and SWANSON and HAILEY, 1987). Over the last few years the size of CT devices and the time taken to assess the internal condition of trees has both been greatly reduced. The presence of cavities or decayed tissue in trees has been found to be associated with the surface temperature of trees and wounds. This phenomenon is based on the use of infra-red technique for the thermal scanning of trees (CATENA *et al.*, 1990).

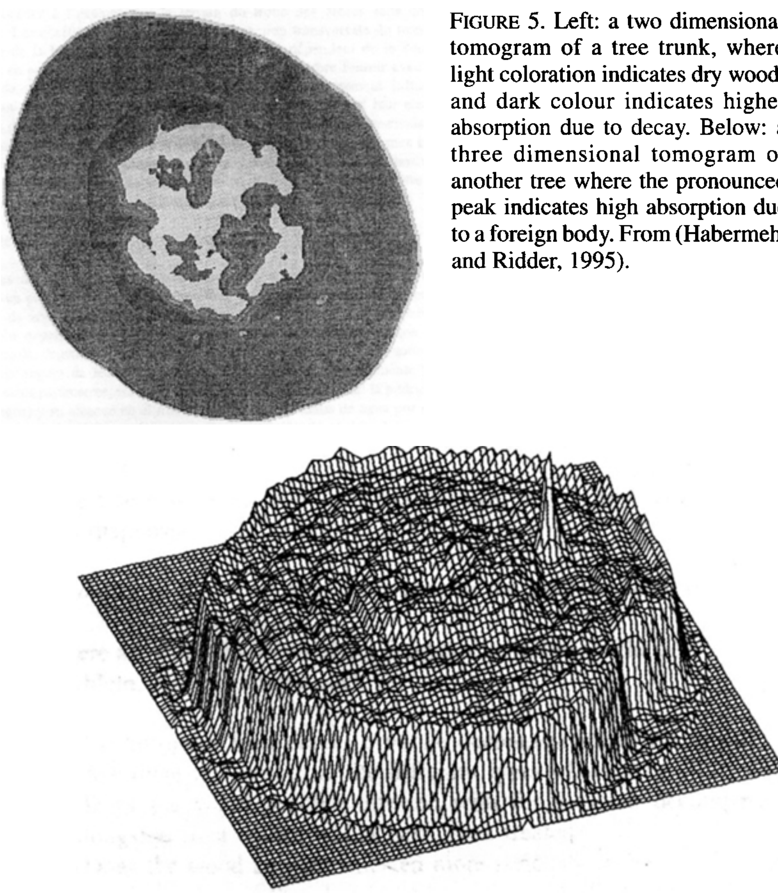


FIGURE 5. Left: a two dimensional tomogram of a tree trunk, where light coloration indicates dry wood, and dark colour indicates higher absorption due to decay. Below: a three dimensional tomogram of another tree where the pronounced peak indicates high absorption due to a foreign body. From (Habermehl and Ridder, 1995).

Despite their accuracy, the techniques described above are not suited for use the forest. The choice of the most appropriate device to determine the internal condition of a tree and to determine the removal of any defect is difficult. The equipment is often cumbersome (some units like X-ray, GPR and CT require a suitable vehicle for their transport to the field); results of the tests take time to be produced (X-ray and CT especially); radiation hazards are associated with some techniques; special training is required in the use of the equipment and the equipment is relatively expensive. The above shortcomings have restricted the use of these techniques in urban and rural streets and parks in cities where old and valuable trees have to be regularly inspected for potential hazards.

Other techniques for investigating the internal condition of tree trunks are based on drilling bore holes into the tree trunk into which a probe is inserted. The *Shigometer* consist of mapping the electrical resistance presented by the

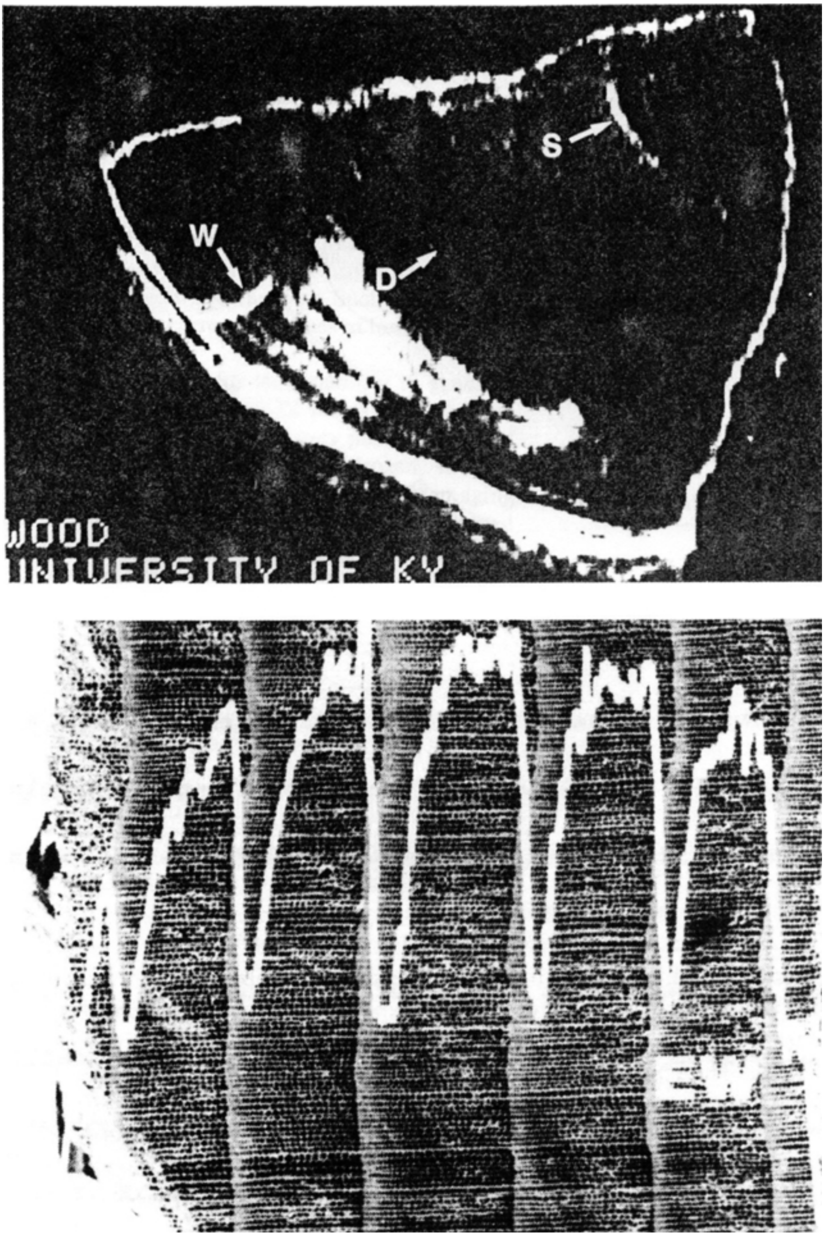


FIGURE 6. Top: cross sectional image of a log using NMR. A worm hole is clearly shown at (W), a ring shake at (S) and a difference between earlywood and latewood at (D), from (Wang and Chang, 1986). Bottom: one dimensional image within growth rings in earlywood, reported by (Swanson and Hailey, 1987).

two needles of the probe along a radius of the trunk, the electrical resistance being lower for sound wood than for decayed wood (SHIGO and SHIGO, 1974; WILKES, 1983; WILSON, 1983). DUNN and ROWLAND (1986) developed a variant of the *Shigometer* and RINN *et al.* (1990) designed the *Resistograph*, a device equipped with a thin core needle of between 1.5mm and 3mm diameter and up to 1m long which is used to measure the resistance penetration of the wood. The results from resistance measurements to penetration have shown reliable correlation with X-ray densitometric measurements. A similar device with a shorter needle, the *Densitomat* has been demonstrated by BEMMANN and KLINGER (1993). MATTHECK *et al.* (1994) and MATTHECK *et al.* 1995) presented the *Fractometer*, a device which subjects a small piece from an increment core of a suspected tree to bending and to measure the force under which failure occurs. Tables of failure values derived from field surveys for different tree species are compared with the results obtained. Wood also presents resistance to shock. The *Pilodyn*, developed in Denmark, uses a hammer blow to measure the shock energy and its penetration into the wood (HOFFMEYER, 1978). This technique has been tested on several types of wood including those trees in which successful decay detection has been reported. Later applications, however have not been recorded. All these methods are destructive, requiring time to drill a hole or to prepare a test sample, both of which are regarded as inadequate for forest conditions. Forest mycological studies have shown that decay in trees release specific chemical substances and SVEDBERG is convinced that dogs are able to smell rot at the base of a decayed tree (DAVNER, 1986).

FIGURE 7. Left: photograph of a portion of a tree. Right: thermogram of the same area. Areas illuminated by the sun are numbered 1. Cavities are indicated by dark (cold) patches. From (Catena et al., 1990).

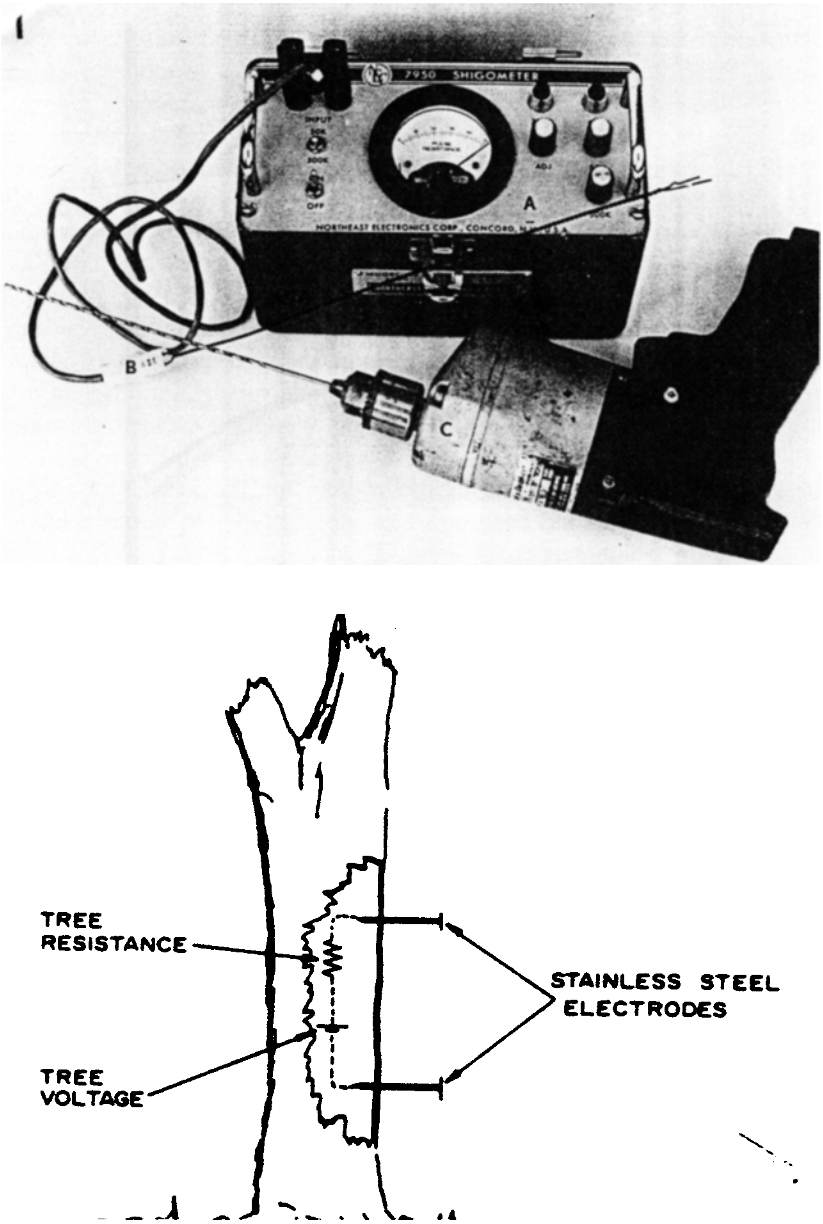


FIGURE 8. The Shigometer. Top: a picture of the apparatus, from (Shigo and Berry, 1975), and bottom: illustration of principle of application on a tree, from (Skutt et al., 1972).

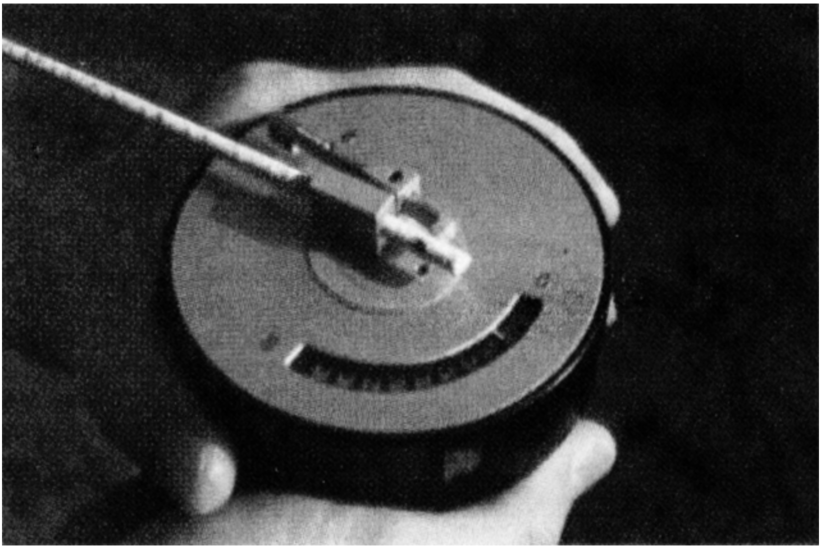


FIGURE 9. A picture of the hand hold Fractometer. From (Rinn, 1996).

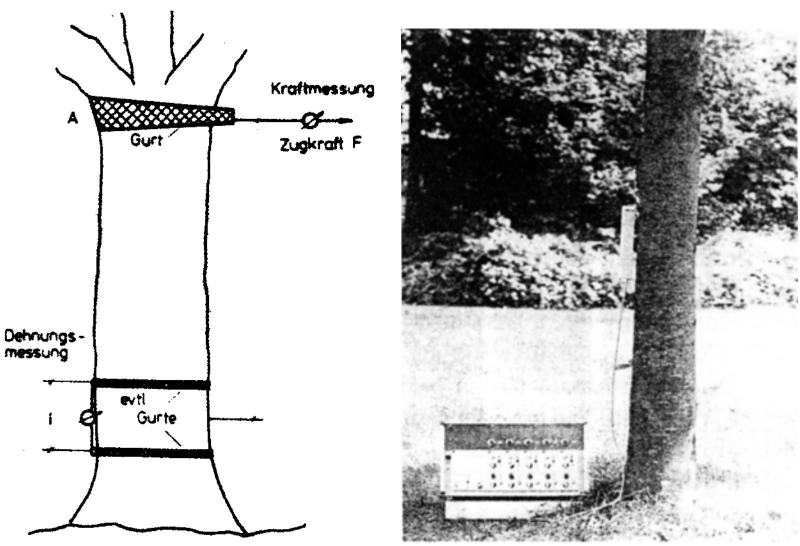


FIGURE 10. The Elastomethode, Left: principle of functioning, right: the method in practice. From (Wessoly, 1988).

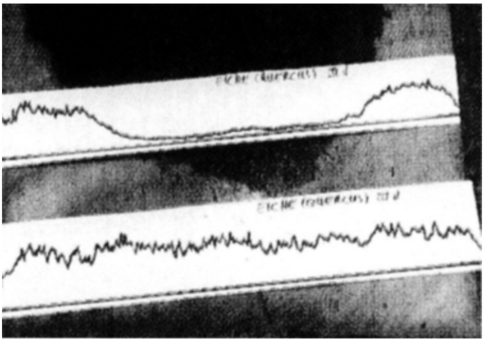
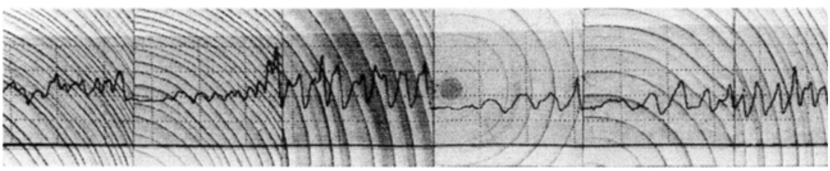


FIGURE 11. Traces from a Resistograph test measurement. left: on construction timber, and below: for dendrochronological purposes. (From Rinn, 1996).



Non destructive detection of decay in wood by vibrations

Vibration methods are commonly used in engineering for assessing the strength of materials and very checking the soundness of structures. Striking a structure to obtain resonance may cause mechanical failure and reduce drastically its life span. As wood is a solid material which is used in a high proportion of built structures, it would be natural to develop and adapt the use of these vibrational methods for testing the mechanical behaviour of wood either as a raw material or as a composite under various physical conditions. Considerable research has been conducted on the mechanical properties of timber and this has been reported over the past 150 years (HEARMON, 1966) even before the development of ultrasonics and radiological scanning techniques. Many researchers have contributed to the understanding of the mechanical behaviour of wood and to quantify its physical properties, its strength for the manufacture of bearings or for its dampening properties to reduce vibrations and for isolating unwanted sound (or the opposite: to intensify sound as in musical instruments). However, wood is a highly anisotropic material which makes its mechanical properties dependant on the direction of the determination. Due to its remarkable heterogeneity even in a small tree, it is impossible to derive a general testing method for wood and the diverse data published in the relevant literature is often derived from average results. The most successful experimental results which strongly support the theoretical predictions, have been conducted on small specimens because the presence of the least defect, in some instances a single knot, may give rise to a wide variation of the value of the parameter being measured (CHUI, 1991; SKATTER, 1996). Much progress has been made over the last few years in the characterisation of wood by non-destructive vibration testing. It seems that vibro-acoustics is again being introduced into the development of testing tools (BODIG and JATNE, 1982; SOBUE 1986a and 1986b).

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Résumé

Cet article passe en revue les différences techniques utilisées pour examiner si le tronc d'un arbre sur pied présente ou non de la pourriture. Les techniques les plus répandues et les plus efficaces peuvent généralement se classer en deux grandes catégories suivant le signal utilisé pour examiner le tronc d'arbre. La première catégorie comprend les techniques vibro-acoustiques ayant recours soit à des vibrations dont les fréquencies s'inscrivent au sein de la largeur de bande acoustique soit à des ondes sonores à fréquences acoustiques ou ultrasoniques. Cette deuxième catégorie de techniques utilise une variété de méthodes basées sur la radiation électromagnétique. Il existe aussi d'autres techniques plus ou moins destructrices, qui sont aussi présentées dans le présent ouvrage. Bien que ces techniques soient destructives, elles le sont moins que celles qui sont très connues et entièrement destructrices, dans le mesure où seul un petit échantillon se trouve extrait du tronc de l'arbre pour être soumis à un examen.