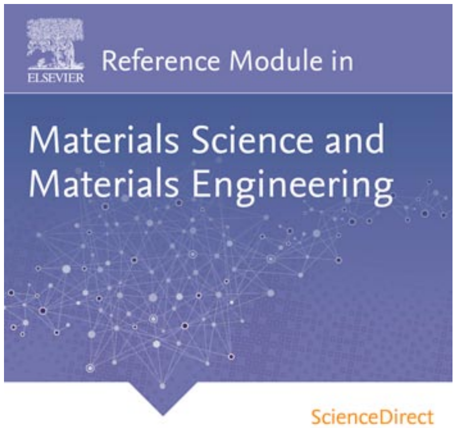

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NDT of Polymers, Cardboard, Wood and Lumber ☆

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1 Introduction

Wood, paper, and polymers are very widely used materials and particularly wood and paper contain quality variations which means that there is a need to use nondestructive testing (NDT) methods or apply quality control on them during manufacturing. The Infrared analysis tools are nowadays widely used for the NDT of composite materials, belonging to many different industrial sectors (Lizaranzu *et al.*, 2015). Of course, wood is used 'as is,' but there still is a need to classify wood and to detect knots in wood planks, which often are regarded as undesirable. All three materials are not easy to test because their structure is complex and particularly their ultrasonic attenuation is high. Paper manufacturing is a very large-scale world-wide industry and the use of paper is ever increasing despite the predictions of the 'paperless office.' However, paper quality control, most desirably, should be on-line noncontact testing. The considered testing methods are the following: ultrasonic (both contacting and noncontacting); optical inspection methods; infrared imaging; thermal wave testing; microwave NDT (Pelivanov *et al.*, 2014; Sarasini and Santulli, 2014); and some radioactive methods. The NDT of fiber-reinforced composites with a new fiber-optic pump–probe laser-ultrasound system. For each material, the applicability of the various NDT methods is discussed.

2 Polymers

Polymers exist in such a multitude of forms that it is pointless to classify them in any kind of order. Nondestructive testing would include microwave (dielectric) testing, optical characterization and microscopy, thermal properties, and finally ultrasonic testing.

Dimensional and elastic properties are best suited for NDT. For example, the thin polymer film thickness could be measured by laser interference in the case of capacitive film manufacture – provided the film is optically transparent. A tricky problem is to be able to measure the film thickness from one side only. A case in point is to determine the wall thickness of PET polymer bottles from the outside only. In this case, a reflective-mode confocal microscope would be suitable.

Elastic properties would include the anisotropy of polymer foils and films. A case in point again is the anisotropy of computer tapes (or similar) which should have minimal elongation properties in the direction of the draw tension. Ultrasonic plate waves similar to the case of paper testing can be used to test the anisotropy. The drawback of ultrasound is yet again the high acoustic attenuation of most polymers, which limits the applicability of ultrasonics.

Carbon reinforced polymer panels are suitable for both ultrasonic and thermal wave testing. Delaminations and poor bonding display themselves as a thermal contrast in photothermal testing. Quality control of critical components manufactured from carbon fiber polymers can be carried out in this fashion.

3 Paper

The PC computer printouts and the printing industry in general are two major users of high-quality paper. Laminated paper is used also in packaging industry and even in making printed circuit boards for consumer electronics. Paper is here to stay and grow despite computer screens. A lot of high-tech research is behind paper making. Consider the latest paper-making machines: the width of the paper strip is 8 m and it is fabricated at top speeds of about 150 km h^{-1}, at 'motorway' speeds!

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The four commonly wanted paper characteristics on-line, on the machine, are: the paper caliber (thickness); the paper square weight; and moisture content of the paper and the distribution or orientation of the paper fibers along the paper plane and also thickness-wise. Also the consistency of the paper slurry is wanted before it is spread on the Fourdrinier wire at high speed. In addition, the draw tension of the paper is also wanted in order to prevent the paper from tearing apart.

The paper caliber is measured mostly with a magnetic contacting probe, which is connected to a microwave resonator by the aid of a connecting rod. A displacement (thickness variation) causes a shift in the microwave resonance and the paper caliber can be calculated with an accuracy of about 1.5 μm with the resolution being much better. This meter is a standard, which is generally used, but it has a contact-making probe, which is a clear drawback.

The paper square weight can be calculated if the caliber and paper density are known. The paper density is obtained with beta-ray absorption and back-scatter measurements which are sensitive to the mass volume of the paper material. There are standard, commercially available beta-ray meters for this purpose. The principles are described in more detail by Lavigne (1985). A surprisingly simple acoustic transmission method based upon first principles can also be used to measure the square weight of paper or similar foils. The through-transmitted acoustic intensity has a direct dependence upon the square weight of paper with excellent resolution as seen in **Figure 1**. The incident sound is generated by an ordinary loudspeaker and the transmitted sound is detected by an ordinary audio microphone (Vuohelainen, 1998).

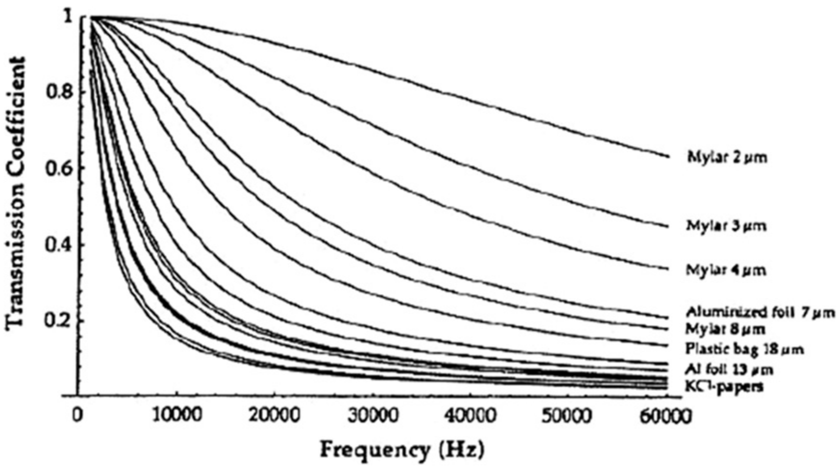

Figure 1 The acoustic transmission vs. foil thickness according to Vuohelainen (1998). Note the excellent resolution at 2–4 μm.

The moisture content of the paper is important and critical, as the customer does not want to pay too much for water in the paper. The maximum allowed water content is 7% of weight. A number of moisture meters have been developed and the most promising are infrared-based meters which measure the absorption of IR light at the water-sensitive band of IR radiation. A major problem is, of course, the elimination of caliber and density variations in the obtained signals. However, a satisfactory instrument has been developed. A largely unsolved problem is the fiber orientation and distribution measurement on-line. The fiber orientation determines the elastic anisotropy of the paper. Of course, the paper strength is determined off-line in the laboratory with standard tear-strength measurements but a knowledge of this variable on-line would be most valuable as the handling characteristics of paper (e.g., newspaper) is largely determined by the anisotropy. (While reading a newspaper, one wants the paper to stand erect in the vertical direction, not to flop over and +over the print.)

A number of systems have been tried, but none of them has made the breakthrough to be used on-line in paper machines. Ultrasound would be a natural system for this anisotropy problem and a couple of measurement instruments have been built which show good promise. A system based on airborne plate wave resonances works quite well where the plate wave velocity is measured in-plane from various directions. The obtained results correlate quite well with the standard mechanical tests. The problem is the implementation of this instrument on the machine, as the paper vibration and noise tends to mask the plate wave resonance phenomenon. The plate wave resonance is created by sending a 80–120 kHz airborne ultrasonic beam at an oblique angle against the paper (or cardboard) and the angle of incidence is varied. An angle is usually found where the ultrasonic transmission through the paper is maximum. At this angle a plate wave is generated in the paper and its velocity can be deduced from the angle of incidence and frequency (Khoury *et al.*, 1998; Luukkala *et al.*, 1971).

The accurate control of the paper slurry consistency at the wet end is quite important as great savings can be obtained. A standard 'sword' type torque arm in the slurry flow has been used, but its dynamic range has been somewhat limited. A system where a microwave beam is transmitted though the slurry is used and the resulting phase velocity shift is measured. The phase velocity variations are an accurate indication of the slurry consistency variations. The instrument is widely used in the paper-making industry as it solves a critical problem with a good accuracy as shown in **Figure 2**.

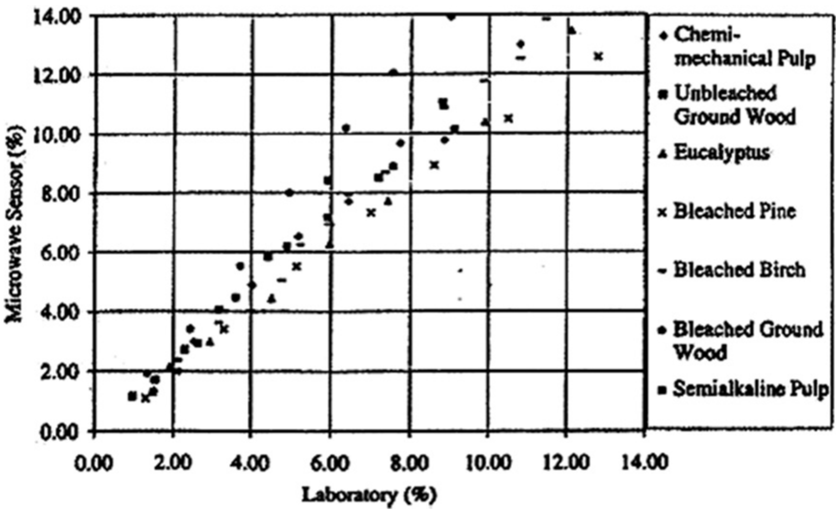

Figure 2 Consistency vs. microwave transmission.

The tensile strength of the paper sheet under production is also a needed quantity. Two methods have been developed to detect the tension variation across the machine direction. One is simply blowing a depression on the paper with a pressurized air jet. The depression depth is a function of the paper tension. By moving the jet across the paper the distribution of the tension is obtained. Another method is to excite a membrane wave in the paper with a loudspeaker at the frequency range of about 100–500 Hz. The propagating membrane wave velocity is a simple function of the tension of the paper if the square mass of the paper is known (as usually is the case).

4 Wood and Lumber

Wood is, of course, one of the oldest construction materials and a lot of 'layman's knowledge' of its properties is known. A composite material made of wood is veneer, which, despite its humbleness, is a surprisingly strong and durable material, particularly in its 'aircraft-quality' form. In general, wood has a very high ultrasonic attenuation, which limits the use of ultrasound to very low frequencies where the wavelength of the ultrasound is so large that its usefulness is questionable. In addition, wood is highly anisotropic so that the velocity of ultrasound along the wood grain is clearly higher than transverse to the grain (Bucur, 1995).

In growing trees there exists a particular disease that makes the trees hollow from bottom up and destroys the quality and usefulness of the wood material. The hollowness in growing trees would be important to detect as the disease might otherwise spread to other trees, but since the attenuation of ultrasound in growing trees is high, ultrasonic detection is not useful. In particular, the spruce tree suffers from this fungal disease.

In small scale testing, ultrasound could be used to investigate the elastic anisotropy of a piece of wood, detect possible defects in glued joints, etc. in a standard way using readily available commercial gear. The homogeneity of the material from sample to sample could thus be monitored. Unfortunately, in general, we have to conclude that there are only limited opportunities for successful NDT of wood. Research into the use of NDT in wood products has been carried out in different areas: the principles of techniques and factors affecting use, the characterization of wood and wood-based materials, the evaluation of forest materials for structural and nonstructural applications, hazard assessment of urban trees and the assessment of existing structures, etc. (Íñiguez-González *et al.*, 2015).

Veneer, which is a layered composite of wood, occasionally suffers delamination of glued layers. Delamination can be detected with straight through-transmission of ultrasound, even in a noncontacting way using airborne low-frequency ultrasound (25–40 kHz). The delamination causes impedance mismatches, which can be registered as additional absorption in the transmitted ultrasound.

5 Conclusion

As a conclusion one might say that better NDT methods are needed particularly for on-line testing, but the development of new and commercially viable methods is quite difficult to make in the foreseeable future. The most likely development is nonlinear ultrasonics and various forms of microscopic methods.

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