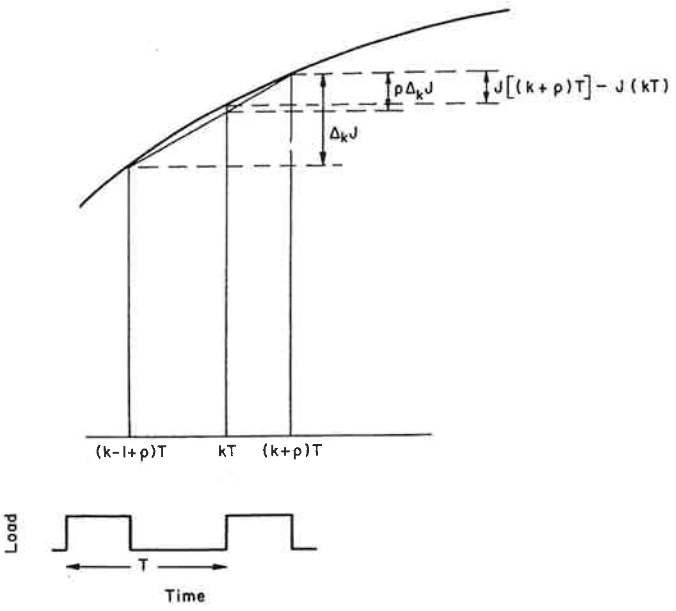

Fig. A1. Illustration of the inequality A4

where

$$\Delta_k J = J((k+\varrho)T) - J((k-1+\varrho)T) \tag{A5}$$

which is the increase in creep compliance J (t) over that interval.

The inequality holds when Eq. (A4) is summed over all intervals from $k=1$ to $k=m$. The left side of the summed inequality is seen, from Eq. (A3), to be the increase in compliance of the intermittently loaded material after the end of the first loading time ϱT. The right side of the summed inequality is ϱ-times the term $\sum \Delta_k J$, the increase of the creep compliance over the same period.

The result derived here for compliances is equally applicable for strains if the effects of intermittent and constant loads of equal magnitude are compared. On the assumption of superposition it has been shown that the excess strain after the first peak at intermittent loading is less than ϱ-times the excess strain over the same period under constant load.

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Evaluation of wood characteristics: Internal scanning of the material by microwaves*

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Summary. Internal scanning of wood by microwaves presents many advantages for the automatic detection of defects and the evaluation of the characteristics of wood in the dry wood processing industries. Advantages are: access to more than one variable, efficient coupling in the air, easy automation and reasonable cost. Microwaves are electromagnetic waves the speed and attenuation of which depend of the medium in which they are propagated, especially its electric permittivity which depends on its moisture content and its density. Since wood is anisotropic, this dielectric constant also varies with the direction of fibers. An experimental apparatus was set up that allows to test the feasibility of automatic detection of wood characteristics and defects. It automatically measures the attenuation and dephasing of an ultra high frequency wave sent through a board and moving through two rotating antennas. The graphs and results obtained gave significant information of physical characteristics of wood (density, moisture content, slope of grain) and the detection of defects (knots, metallic objects, sapwood).

Introduction

In the past few years, methods of automating and mechanizing wood industries have been developing. This development should increase because of decreases in cost of computing and the necessity of increasing the productivity and the flexibility of industries.

If some part of new technologies, adopted by other industries, can be rapidly transferred to the wood industries, the lack of sensors for observing dimensional and qualitative characteristics of the material prevented wood industries from adopting new technologies developed in other industries.

On the other hand, an economic use of wood as a resistant material is anticipated (industrial carpentry, laminated beams), and this is related to an increase in the cost of the raw material, which may be 45% of the cost of the finished product. The accurate evaluation of the mechanical and physical characteristics of the material, often related to density, moisture content or slope of grain, need the set up of a systematic quality control of the material by the manufactures.

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In order to evaluate the moisture content or the density of different materials (wheat, sand, coal, tobacco etc.), some devices of automatic control have been developed (Meyer, Schilz 1980; Klein 1981), which are based on the dielectric constant of these materials. The speed and attenuation of electromagnetic waves propagating in any medium depend on the nature of this medium, and especially on the coefficient of electric permittivity ε also called dielectric constant of these materials. The dielectric constant is a complex number $\varepsilon^* = \varepsilon' - j\varepsilon''$, in order to illustrate the dissipating effects like absorption of energy by the water molecules. So, the behavior of the dielectric material is determined by a capacity in parallel with a resistance:

$$I = (j\,\omega\,\varepsilon' + \omega\,\varepsilon'')\,Co = j\,\omega\,\varepsilon^*\,Co\,(V)$$

where:

I = total current accross material
Co = capacity of the condenser capacity
ε = relative permittivity of the material.

As far as wood is concerned, some researchers (Tiuri et al. 1985; James, Hamill 1965; Peyskens et al. 1984; James et al. 1985) have found that, with wood, for frequencies up to 10 GHz, the dielectric constant increases when density, moisture content or temperature increase, but decreases when the frequency is increased. In the case of a low wood moisture content (below fiber saturation point), and at frequencies close to 10 GHz, ε'' is small compared with ε', and in these conditions, the effect of density is more important for ε', while tg ($tg = \varepsilon''/\varepsilon'$) is more sensitive to humidity. So, a variation in density could be estimated from a variation in the phase of a wave being propagated across the material, while a variation in moisture content could be estimated by a variation in attenuation of this wave. Moreover, wood is anisotropic, and it is noticeable that the dielectric constant is greater or smaller if the electric field is parallel or perpendicular to the fiber direction. When the electric field is in a transverse plane to the fibers, the value of the dielectic constant is higher in tangential direction compared with radial direction. But, the difference in this case is less important than the difference found between longitudinal and transverse directions.

Wood is a dielectric material of the most general class of dielectrics, it is also anisotropic and it has losses. These dielectric properties are expressed through a tensor of rank two of complex components. This tensor is reduced to three diagonal complex coefficients if the space is given by the principal axes of the material in longitudinal, tangential and radial direction.

That is why, a polarised incident electromagnetic wave is depolarised, after transmission through the material, or after reflection on one of its faces, if the polarization plane is not coinciding with one of the three principal directions of anisotropy.

From these considerations, an experimental set up that can be used to determine the physical characteristics of wood (density, moisture content and slope of grain) from the estimation of attenuation, dephasing, and degree of polarization of microwaves has been developed.

Study and set-up of the experimental apparatus

Advantages of a microwave detection

Compared with other techniques of internal detection (X-rays, γ-rays, ultra sounds), microwaves show the following advantages:

- solid technical and theoretical basis, which provides a better interpretation and easier analysis of the signals,
- access to many variables: magnitude, phase, degree of depolarization of the signal, allowing a differenciation of anomalies,
- efficient coupling in the air, from the antennas to the material,
- easy automation,
- not cumbersome, and relatively non expensive materials,
- material is not altered (at lower power) and there is no danger for users.

J. R. King (1978) has shown that it is feasible to measure in real time the magnitude, phase, and depolarization of microwaves transmitted through wood.

Description of the set-up

The main components of the experimental set-up are shown in Fig. 1. A source of continuous microwaves produces an electromagnetic wave of low power (about 5 mV). Its frequency is set at 9,245 MHz (3.24 cm). The source used is a Klystron

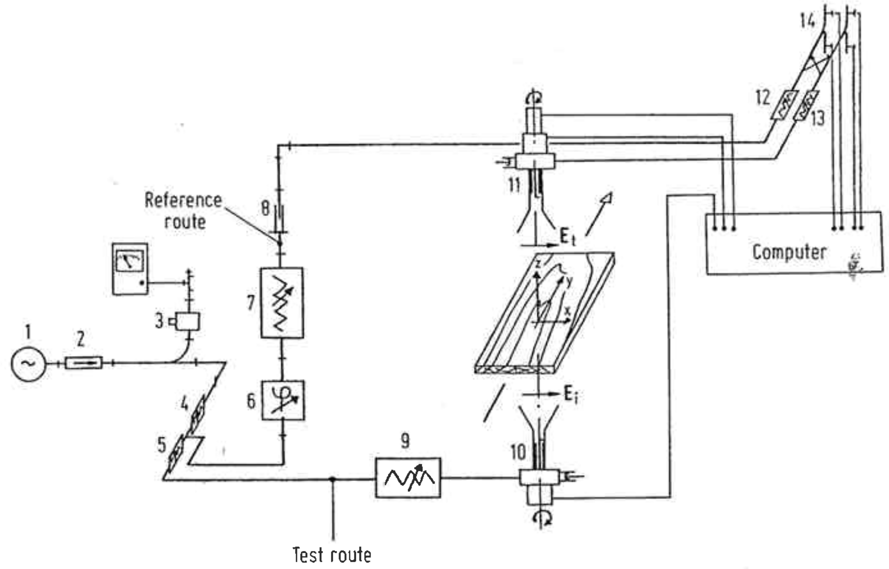

Fig. 1. Scheme of the set-up. 1 source (9,245 Mhz); 2 mono-directional line; 3 wavemeter; 4; 5; 7; 12; 13 attenuator; 6 calibrated static phase shifter; 8 sliding linkage; 9 calibrated attenuator; 10; 11 antenna; 14 measuring head

reflex. The emitted wave is propagated inside of the material, according to the mode TE 10 (electric field perpendicular to the direction of propagation).

A unidirectional line (2) is placed right after the source, in order to isolate the Klystron from the rest of the circuit. Then, a fraction of the wave is passed through the intermediate of a coupler, in order to control the power and the value of the frequency as it goes through a wavemeter (3). There are six attenuators; one is calibrated to regulate the levels of power in the different circuits of the set-up. The power is estimated by comparison with a reference attenuator. A first attenuator (4) is placed, so that the power of the installation is limited when the experiment is not being used.

Part of the wave is transmitted through the material, then it is recombined with the part of the set-up whose function is a reference at the level of a measuring head (14). A static phase shifter (6) and 2 attenuators (5; 12; 13) play the role of adaptation of impedance. The antennas (10; 11) on the test route are polarized, and it is possible to turn their polarization by engines operated from a computer. Finally, a sliding linkage (8) was used to easily modify the distance between the antennas.

Therefore, the principle used is a measuring bridge, which is sensitive to the measurements being made. The measuring head used has the advantage of giving four signals from four detectors, and these signals are proportional to the vectorial sum of the electric field of each way with a dephasing of $\pi/2$ between each detector. A system of four equations with three unknows is then obtained. The unknows are A and B, which represent the attentuation of each way with a dephasing. Because this system is super abundant, a relation of compatibility allows to test how well the sensors work.

Automation of the set-up

The objective was to produce an experimental set-up which would have a sufficient degree of automatization in order to facilitate the experiment in the laboratory, and to better know the feasibility of the method in the industry.

Thus, the system developed:

- gave accurate values of attenuation and dephasing, the data being processed by a computer,
- insured the rotation of the polarization plane,
- analysed many samples, and therefore tested the repeatibility of the measures,
- visualized the results through graphs and curves.

A Goupil III microcomputer was used with a printer and a supplementary screen (the screen of the basic system was used as a service console). An analog to digital card and an casing box for adapting the signals insured the linkage between the microcomputer and the set-up. Two step-by-step engines allowed the antennas to rotate and one of them was coupled to a pulse machine to initialize the orientation of the antennas at the beginning of the experiment. A third step-by-step engine was used to move the board to be analyzed. The three engines were controlled by the computer through the interface.

An analog to a digital card with programmable gain, and a box made in the laboratory insured the interface. The box placed the necessary components between the analog to the digital converter and the detectors, to insure that the system worked well. At this point, a difficulty was encountered due to non linearity and difference in sensitivity of the detectors. An adjustment of reponse was necessary, and this was done by charging impedances and adjusting resistances. For the whole set-up, the ratio of the noise over the obtained signl was around 1%, which was very satisfactory for our experiments.

A program for the acquisition of the signals and of the system of equations giving A, B and φ was made. Mathematically, the non-linearity of the equations and the introduction of correction coefficients made the analytical computation of the solutions impossible, therefore the solutions were obtained through numerical resolution. The visualization of the curves of variations of A, B and φ or of the slope of grain, being functions of the board position was assured. Two programs of application were made:

- the first one allowed the analysis of irregularities, by visualizing the magnitude of the electric fields of the two ways of the bridge and of their dephasing, for successive movement of the samples, without moving the antennas;
- the second program evaluated the slope of grain in boards without defects or traces, on the graphic screen. The average curvature of the fibers was deducted from the position of the antennas corresponding to the best transmission. For each successive position of the board, this orientation was determined only through the dephasing, which was more sensitive than the magnitude to variations in slope of grain.

Results

Influence of density

In order to have enough density differences, wood from different species (hardwoods and softwoods) was used. These boards, after being stored long enough under the same conditions and sheltered against weather, were air dried, until their moisture contents were close. To use these species for comparison, they were planed to a constant thickness (18 mm). Their density was evaluated from small samples taken from these boards.

The same adjustments of the bridge were kept during the analysis of all boards. For the study, the programme of analysis of irregularities was used, and the samples were scanned on a length of 250 mm, memorizing the values of B and φ every 5 mm. When some singularities were found during the experiment, the corresponding value was eliminated, so that variations due to irregularities were avoided.

Comparison of the variances of B and φ for each sample and from sample to sample showed that their averages were significantly different. This allowed the study of the relationship between the variations of B and density.

A very significant relationship between phase shift and specific gravity (= density) was found with a coefficient of correlation r of 0,87. A regression line was thus determined with a slope s = 107 (Fig. 2 a).

However, no significant relationship between the average values of B and density was found (r = 0,02) (Fig. 2 b).

The confirmation of the relationship between φ and density by other experiments, and a formal proof by a theoretical study would allow the development of a procedure that could be used in industry to continuously evaluate the density of the material.

This is particularly interesting for use in monitoring the mechanical resistance of wood. The standard NF B 52 00 gives the minimal density required (0.5 for softwoods and 0.8 for hardwoods) in constructions. Woods used in industrial joinery must have a minimal density. When dry boards are to be taken delivery, this non destructive and quick method could be used to eliminate boards that don't meet the standards before they are processed. This would be particularly applicable to tropical woods which may contain many different species and are often difficult to identify.

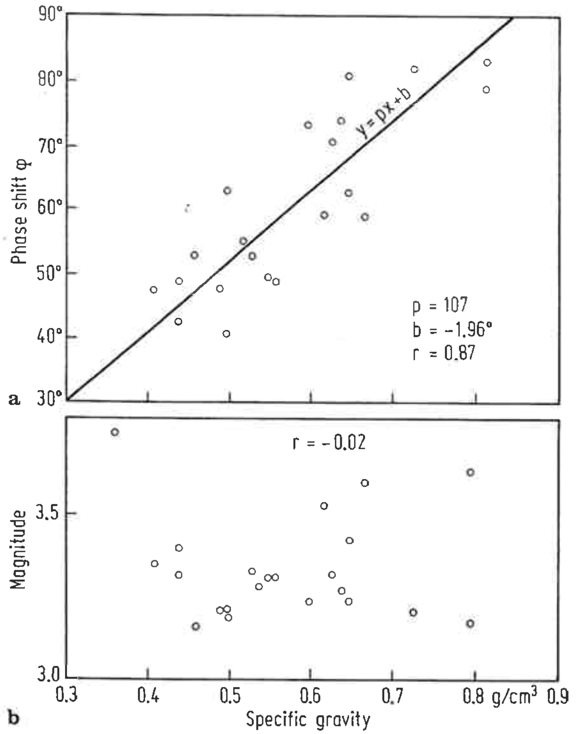

Fig. 2. Variation of **a)** the phase shift, **b)** the magnitude, with specific gravity

Influence of moisture content

The study of the influence of moisture content on the parameters B and φ was limited, because of the lack of necessary materials.

However, Fig. 3 shows that these parameters vary with moisture content. It was possible to observe moisture content profiles between the middle of the board and its extremities, which were related to the differences in wood drying rate. It was also possible to notice the development of the moisture content in the sample for an analysis made at different times, in intervals of more than one month.

Influence of slope of grain

Figure 4 a shows the curves of φ as a function of the orientation (α) of the antennas at two different places of an oak board where the inclination of the fibers (ψ) has changed. The angular variation $\Delta\alpha$, relative to the position of the maxima of φ of the two curves, almost corresponds to the slope of grain $\Delta\psi$, measured on the board.

Using the specific program, the curves giving the slope of grain were obtained without defect (Fig. 4 b).

Within this method, the measurement of the slope of grain can be made with a precision of 2 to 3°. A quick scanning, thanks to the use of electronic rotating antennas, could produce a sensor suitable at industrial speed.

Knots detection

Figures 5 and 6 show the good sensitivity of the phase and of the attenuation with oak and pine boards, when little knots go through (5 to 10 mm). The quality of the surface of the material did not interfere with the detection in unplaned boards.

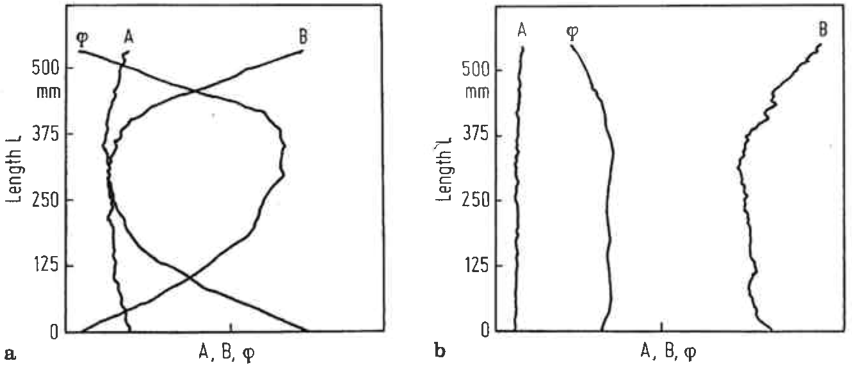

Fig. 3. Variation of B (mV) and phase shift φ (°) along the board length L. Analysis at different times **a)** 26. 8. 83 and **b)** 22. 9. 83

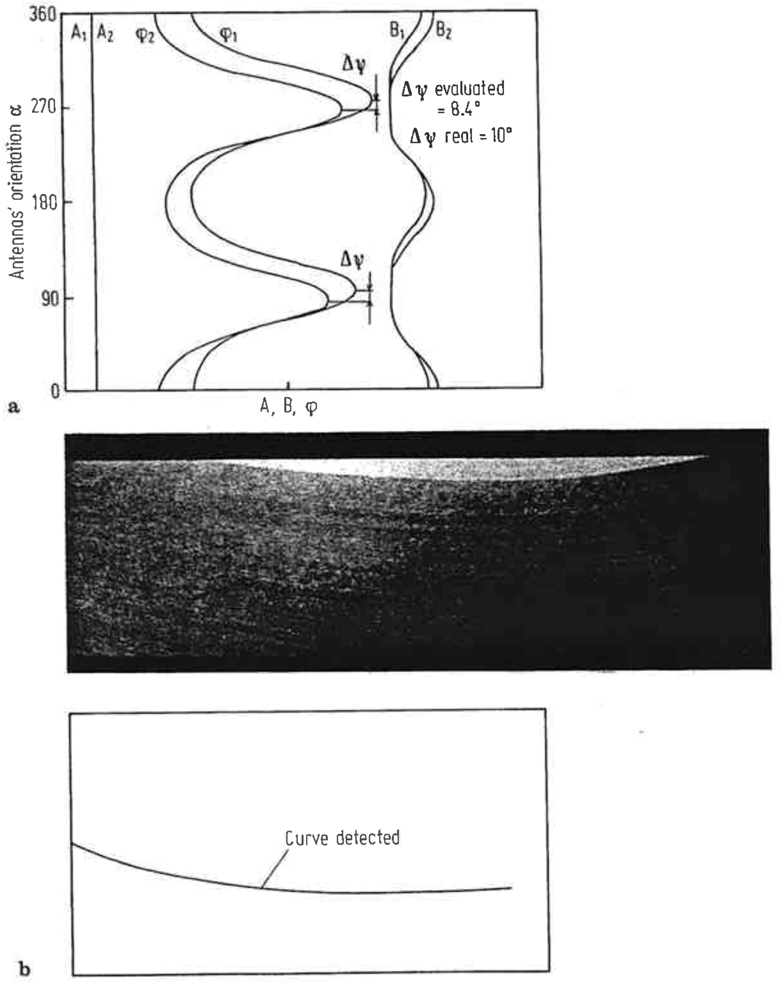

Fig. 4. **a** Slope of the grain evaluation between two points; **b** Oak; mean slope of grain evaluation

On all curves obtained, it was noticeable that the maximum value of dephasing almost corresponded to the middle of the knot, and its magnitude was related to the size of the defect. If there was a knot, the characteristic of the attenuation, was more complex, but seemed to depend on the thickness of the sample and on the position of the defect, compared with the center of the antennas in the width of the board.

For freshly sawn samples, the moisture content hid the variation of parameters, and did not allow the detection of knots, particularly of small diameter.

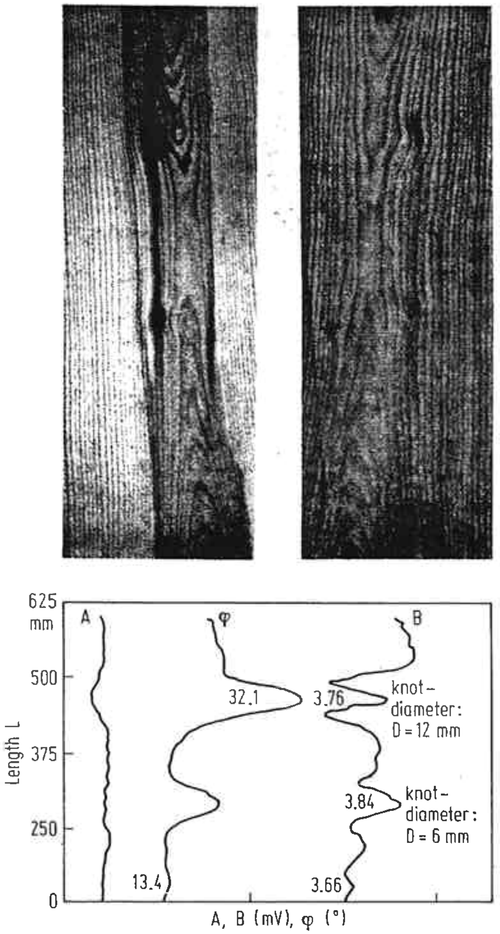

Fig. 5. Knot detection in pine (*Pinus pinaster*)

Detection of other defects

Metallic objects were well detected. Other defects (splits, resin pitches, wormholes, sapwood, wanes) were not detected or had not been properly detected because of the dimension of the antennas used and/or the localization of the defects on the edge of the boards.

However, from reconstituted samples where the heartwood was in the centre of the board, a variation of B and φ, the functions of this singularity, was noticed.

Conclusions

It is well known that the wood characteristics (density, moisture content, slope of grain, etc.) sensitively influence the parameters of microwaves (phase, at-

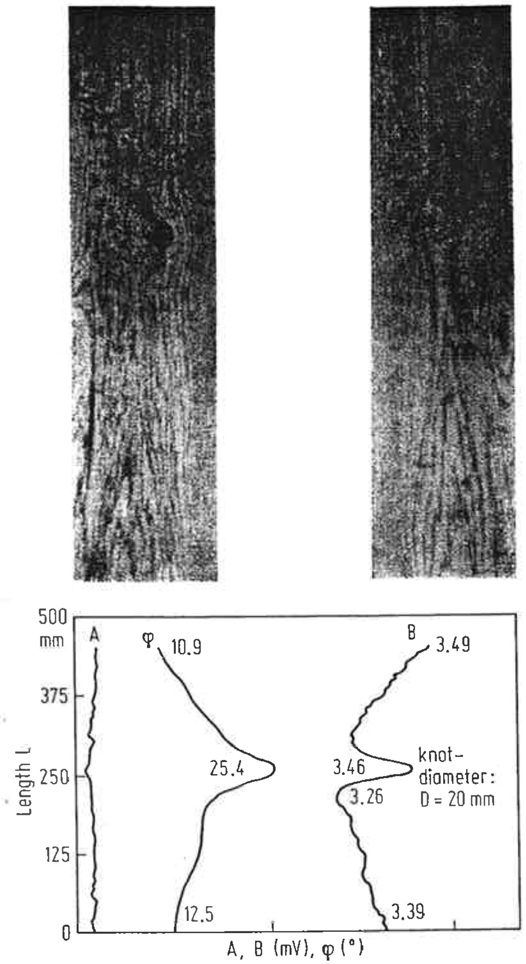

Fig. 6. Knot detection in oak

tenuation, degree of polarization) which go through a board (Tiuri et al. 1980; James, Hamill 1965; James et al. 1985).

From these results an experimental apparatus has been develop in order to detect wood defects and characteristics in a movable board and to test the industrial feasability.

The curves showed that knots and metallic objects were well detected with this method. The smaller singularities as wormholes or small splits, because not obvious.

The surface quality did not interfere with the results. This makes it possible to analyse unplaned boards. When the moisture content of wood became too high (above the fiber saturation point), its influence on measured values was more important. However, this phenomenon does not limit the applicability of this method for the processing of dry wood.

The information on the detection of defects is, up till now, qualitative. Some quantitative results will be obtained by the analysis of signals and the interpretation of curves.

Because of the large amount of variations in wood, and the many defects in the wood, the complete identification of defects and the classification of boards necessitate the use of more than one sensor. The development of this procedure will require additional research with computer analysis, sensor technology, and a better understanding of the physical characteristics of irregularities.

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