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MEASUREMENT OF WOOD STRUCTURAL FEATURES BY OPTICAL TECHNIQUES

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A b s t r a c t. Wood has a structure in which there are multiple regularities, sometimes similar to diffraction gratings. For instance when observing softwood in a transverse view, a bidimensional structure formed by wood tracheids appears. This structure is not homogeneus because of the decreasing size of tracheids near the limit of growth rings, and the eventual existence of other elements like resin canals. In radial view other structures appear, when tracheids intersect wood rays. The intrinsic variability of biological materials reduces the regularities to small zones.

These types of structure allow the use of optical methods to determine the sizes of the distinguishable elements. Diffraction patterns are formed when laser light strikes a thin film of wood. From these patterns information about the structure of wood is obtained. Laser light is specially suitable for this purpose because of its high monochromaticity, directivity and power.

The facts mentioned above are the basis of some devices which allow interesting measurements to be made. For example it would be possible to automate the determination of ring-width, that contains climatic information.

K e y w o r d s: wood structure, optical techniques

INTRODUCTION

The increasing importance that nowadays the ring counting technique to carry out climatic forecasting has and the influence that weather changes have on the microscopic structure of wood leads to develop new analysis methods that allow fast and accurate evaluation of physical parameters of interest in the annual tree-ring structure [1].

One of the techniques that could be of interest in this field is the so-called Optical Image Processing (OIP), [2]. The enormous advances in computer sciences and the possibility to use laser as a source of light easily makes possible the application of these techniques to evaluate not only the tree-ring width, but also the internal structure of tracheids within the rings (ring-width, cell sizes, cell wall growth, etc.).

Our aim is to analyse the applicability of OIP techniques to expose the existence of tree-ring growth of different wood species by means of the analysis of the spatial tracheids periodicity in latewood and earlywood near a ring limit. As a consequence, it is also possible to obtain a qualitative additional information about the dimensions and spatial periodicity of wood structures. In the present work we have used the Diffraction Technique to evaluate tracheids periodicity.

MATERIALS AND METHODS

Tree trunk structure

Tree trunk is a structure that supports the tree and also has the important function of conducting water and nutrients from root to leaves [3].

Trunk structure, from outside to inside consists of the following elements (Fig.1): outer bark, inner bark, cambium, sapwood, heartwood. Either in sapwood or heartwood the annual tree-rings are observed and distinguished because of the presence of two zones which have different colours: earlywood and latewood.

These elements are common to all kinds of wood, i.e., hardwood and softwood. On the other hand these kinds of wood show some differences. Softwood has long fibers, with diameters of decreasing size from earlywood to latewood. Other structures such as resin canals and medular rays are observed.

Hardwood is usually formed by long fibers of small diameter and other cells,

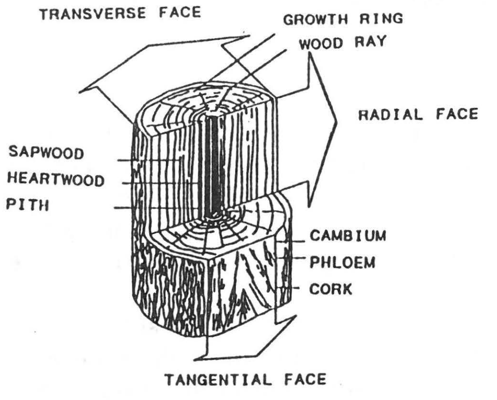


Fig. 1. Tree trunk structure.

shorter and wider, called vessels. There are also vertical and radial parenchyma. It is not always possible to determine the limit of the annual tree-rings, because of the small difference in cell diameter.

DIFFRACTION THEORY

As it is well known, when a wave front which is generated at a source and propagates whithout perturbation, a phenomenon called Wave Front Diffraction takes place if there is a local variation of the amplitude or the wave phase. If phase or amplitude variation is due to an interposed object, this one is called the Diffracting Object [4,5].

On the basis of the approach given by the escalar theory, considering Huygens-Fresnel principle and applying the Kirchhoff theorem, the integral equation of diffraction is thus obtained. From this equation it is possible to calculate the electrical field amplitude (E_p) at any point P, when the position of the source S and the features of the diffracting object are known.

If we consider that the dimensions of the diffracting object are small compared to the distance from the object to the source and to the point, the equation is simplified and the Fraunhofer expression is thus obtained. The general form of this expression is [4,5]:

$$E_p = Q \int_\Sigma E(\zeta,\eta)\, e^{-ik[(\alpha-\alpha')\zeta+(\beta-\beta')\eta]} \quad (1)$$

where $E(\zeta,\eta)$ is called object function and represents the distribution of amplitudes of the diffracting object; α, β, α', and β' are the director cosines of the source point S and the observation point P, referred to the origin; Q takes into account the constants which have not interest for our discussion; K is $2\pi/\lambda$ where λ is the wavelength of the incident radiation; Σ is the integrating surface, (Fig. 2).

The complex exponential term which appears in the integral, is the same that would be obtained if the Fourier Transform was applied. The conclusion is that the intensity space distribution, when the diffracting object is present, can be calculated by the Fourier Transform of the object function, assuming the Fraunhofer approach.

On the other hand, if either the distance between the object and the point or the wavelength is of the same order of magnitude as the dimensions of the diffracting object, Fraunhofer approach is not good

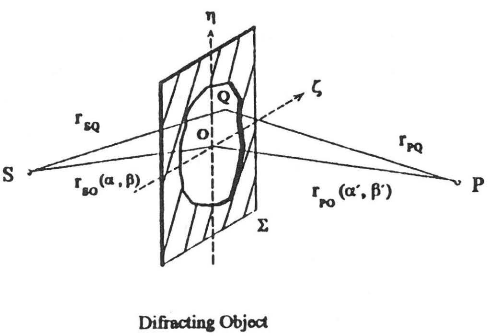


Fig. 2. Geometry used in the evaluation of the Integral Equation of Diffraction.

and it is necessary to calculate the integral. We are now using the Fresnel approach. In this work, due to the diffracting objects dimensions and the distances among the elements, Fraunhofer approach can always be applied, simplifying the calculations and leading to interesting conclusions.

Up to now we have considered the computation of the electric field of the electromagnetic wave at any point *P*. Most times the magnitude that we are interested in is the intensity at the point, obtained in the following way:

$$I_p = \frac{8\pi}{c\,n} \mid E_p \mid^2 \qquad (2)$$

where *c* is the speed of light and *n* is the refraction index of the propagation medium.

So we conclude that the square of the Fourier Transform of the object function, also called frequency spectrum of the function, represents the intensity space distribution. The properties of the Fourier Transform allow us to obtain the shape and other features of an object, if we know the diffraction pattern.

If the diffracting object is a slit of dimensions 2*a* x 2*b* and we suppose that the radiation is collimated, the intensity distribution at any point is given by:

$$I_p = \left[\frac{\sin(2a\,\frac{X_p}{\lambda Z_p})\,\sin(2b\,\frac{Y_p}{\lambda Z_p})}{(2a\,\frac{X_p}{\lambda Z_p})\,(2b\,\frac{Y_p}{\lambda Z_p})} \right]^2 \qquad (3)$$

where X_p, Y_p, Z_p are the coordinates of the point at which we want to calculate the intensity I_p. This expression is the Fourier Transform of the slit function and from its analysis we conclude the presence of regions with maximum and minimum intensity.

A periodic distribution of slit functions is called Diffraction Grating and the intensity at any point will be the Fourier Transform of the Object Function. Diffraction gratings create patterns characterized by the presence of principal maxima, auxiliary maxima and minima. In the case of a periodic monodimensional grating, the expression that gives the direction of principal maxima is:

$$2\,d \sin(\varphi) = m\,\lambda \qquad (4)$$

where λ is the wavelength of the incident radiation, φ the angle for the maximum, *d* the space period of each slit of the grating and *m* an integer value that represents the order of the diffraction maximum. This expression is known as the grating equation.

EXPERIMENTAL

In this work we have studied different kinds of softwood species: *Picea abies, Pinus nigra and Cupressus sempervirens*. A microtome was used to get the most characteristic sections of each sample (i.e., radial, tangential and transverse sections). Then, these samples were stained using floroglucine. The thin film of wood obtained makes possible not only to observe the diffraction pattern produced when the laser light strikes on it, but also it is possible to observe these samples using the optical microscope.

In keeping with the aim of this work we have focused our attention on the transverse sections of the samples from which it is possible to study the annual tree-ring growth.

The experimental procedure is based on a straightforward setup of Optical Signal Processing (Fig. 3) which allows the analysis of the diffraction pattern obtained when the laser light strikes one of the samples mentioned above (diffracting object). We have used a laser as illumination source because of its high light intensity power, monochromaticity and low divergence that allows sampling beam sizes of less than 1 mm. In our case, the laser was a 0.5 mW He-Ne laser with 0.1 mrad of divergence and with a spot beam size of 1 mm.

Samples were placed in an X-Y micrometric table stage and the laser beam struck perpendicular to the sample plane. The light diffracted by the sample was observed through a translucent screen and then we took a photographic picture of these diffraction patterns. The use of an accurate

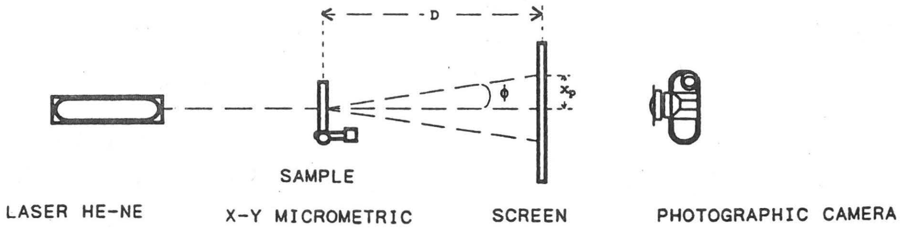


Fig. 3. Experimental setup.

X-Y stage system allowed us to analyse the changes in the diffraction patterns induced when the sample was moved perpendicular to the laser beam and, at the same time, perpendicular to the annual ring. The spatial periodicity of both earlywood and latewood was then easily studied.

RESULTS AND MODELLING

Using the technique described above, we have analysed the transverse, radial and tangential view of some species of softwood and hardwood. Only the transverse and the radial views of softwood show diffraction patterns regular to study cell structures.

Figure 4a shows the bidimensional periodic structures that appear using an optical microscope, from a *Picea abies* sample. Changes in spatial periods are observed at the transition from earlywood to latewood, normally to tree-ring limits. This fact causes changes in the periodicity of diffraction patterns obtained from tracheids, which are different in earlywood and latewood (Fig. 4b and 4c).

The distance between maxima of intensity in the diffraction patterns enables one to detect the transition from one tree-ring to another.

Diffraction patterns are the Fourier Transform of the structures in the tree-ring. It is important to realize that these patterns present zones of maximum and minimum intensity only at the direction of the so-called frequency axis (U) but not at the other (V). This fact is due to the space distribution of tracheids (Fig. 4a): spatial periods along the Y-axis (normal to tree-ring limit) are more stable than those which are along the X-axis (parallel to tree-ring limit).

Diffraction patterns from other softwood species as *Pinus nigra* and *Cupressus sempervirens* have been obtained, giving similar results to those described above.

The existence of zones of maximum and minimum intensity in the diffraction patterns makes possible the calculation of the average of spatial periods of tracheids, at any place of the tree-ring. With this aim we have considered that the distribution of maxima of intensity along the frequency axis (U) is due to the periodicity of tracheids, normal to the tree-ring, that behave as a monodimensional diffraction grating. Therefore the distance between the tracheids centres can be considered the diffraction grating period ($2d$), and Eq. (4) can be used to calculate the sizes at a first approach.

Table 1 shows the values of these distances, calculated from the expression for the diffraction grating, and the values of the distances measured in the sample, using the optical microscope. The agreement between these values is good and this fact confirms the viability of these optical techniques to determine cell parameters.

We have not considered in the above discussion the effect that could cause the existence of some internal components of tracheids which could be transparent and would not be observed, but could behave as diffraction gratings, creating patterns that overlapped the patterns of interest. To clarify this fact and verify the hypothesis that

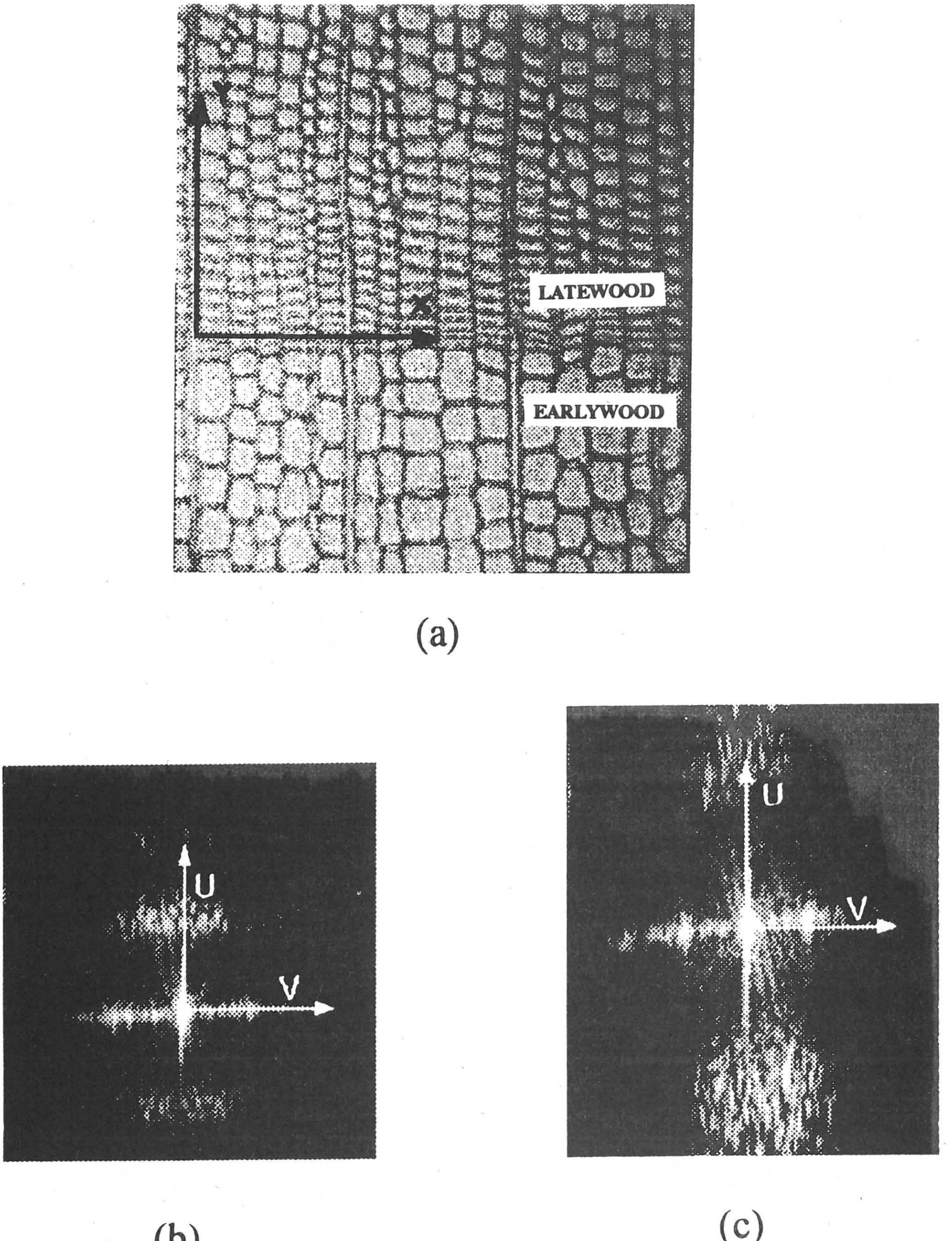
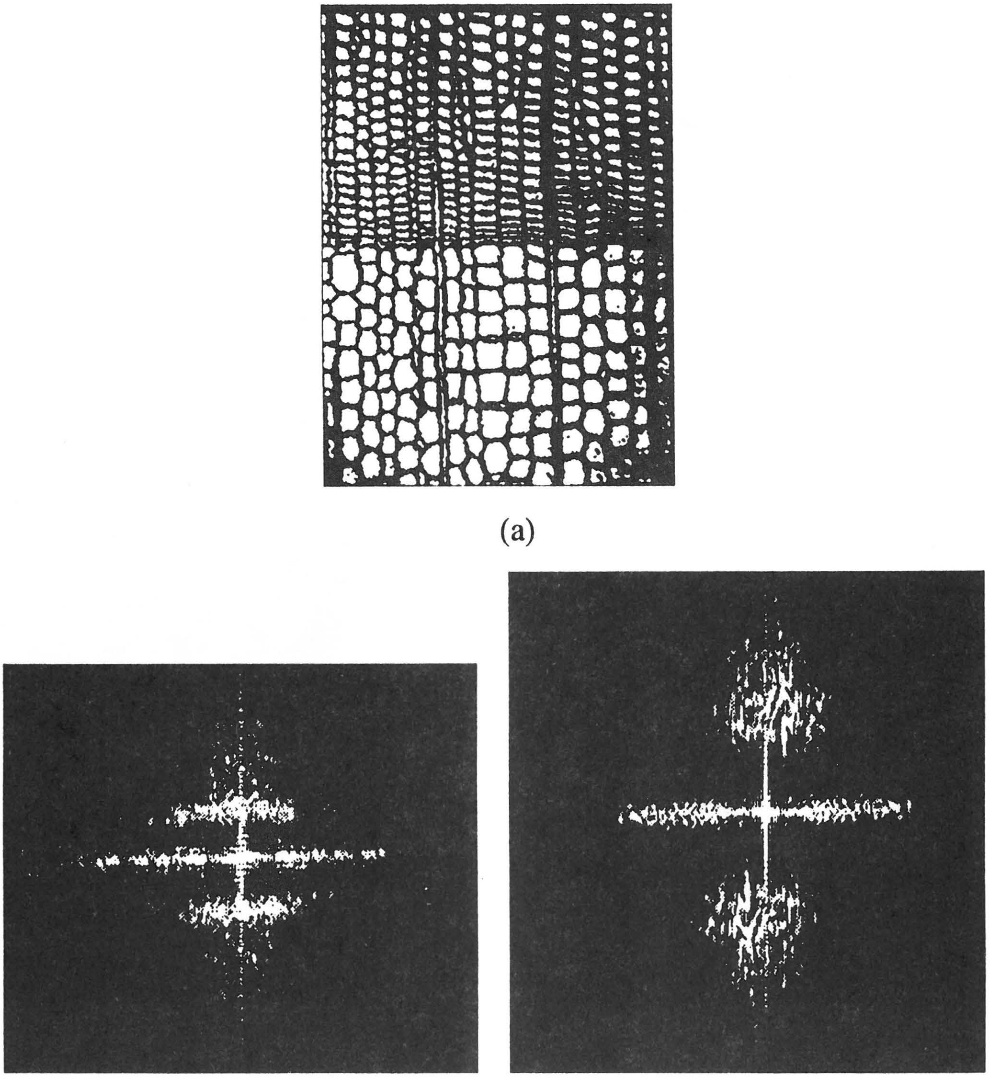


Fig. 4: Transverse view of wood from Picea abies (a). Diffraction patterns obtained from a Picea abies sample earlywood (b) and latewood (c).

tracheids behave as diffraction gratings in amplitude neglecting phase terms, we wrote a computer program using PASCAL, that performs the bidimensional Fast Fourier Transform of digitized pictures.

These pictures (512 x 512 pixels with 256 grey levels) were analysed using Digital Image Processing techniques [6] to obtain thresholds of the cell structures of interest (Fig. 5a). The result obtained after the application of the bidimensional FFT to these patterns is shown in Fig. 5b and 5c, and they are similar to the patterns obtained experimentally (Fig. 4b and 4c). This fact confirms our initial hypothesis: it is possible to consider tracheids as amplitude diffracting objects.

On the other hand, we have studied the radial view of the samples. In some zones,



(a)

(b) (c)

Fig. 5. Digitalized picture obtained from Picea abies in a transverse section (a). Diffraction patterns obtained using FFT at earlywood (b) and at latewood (c).

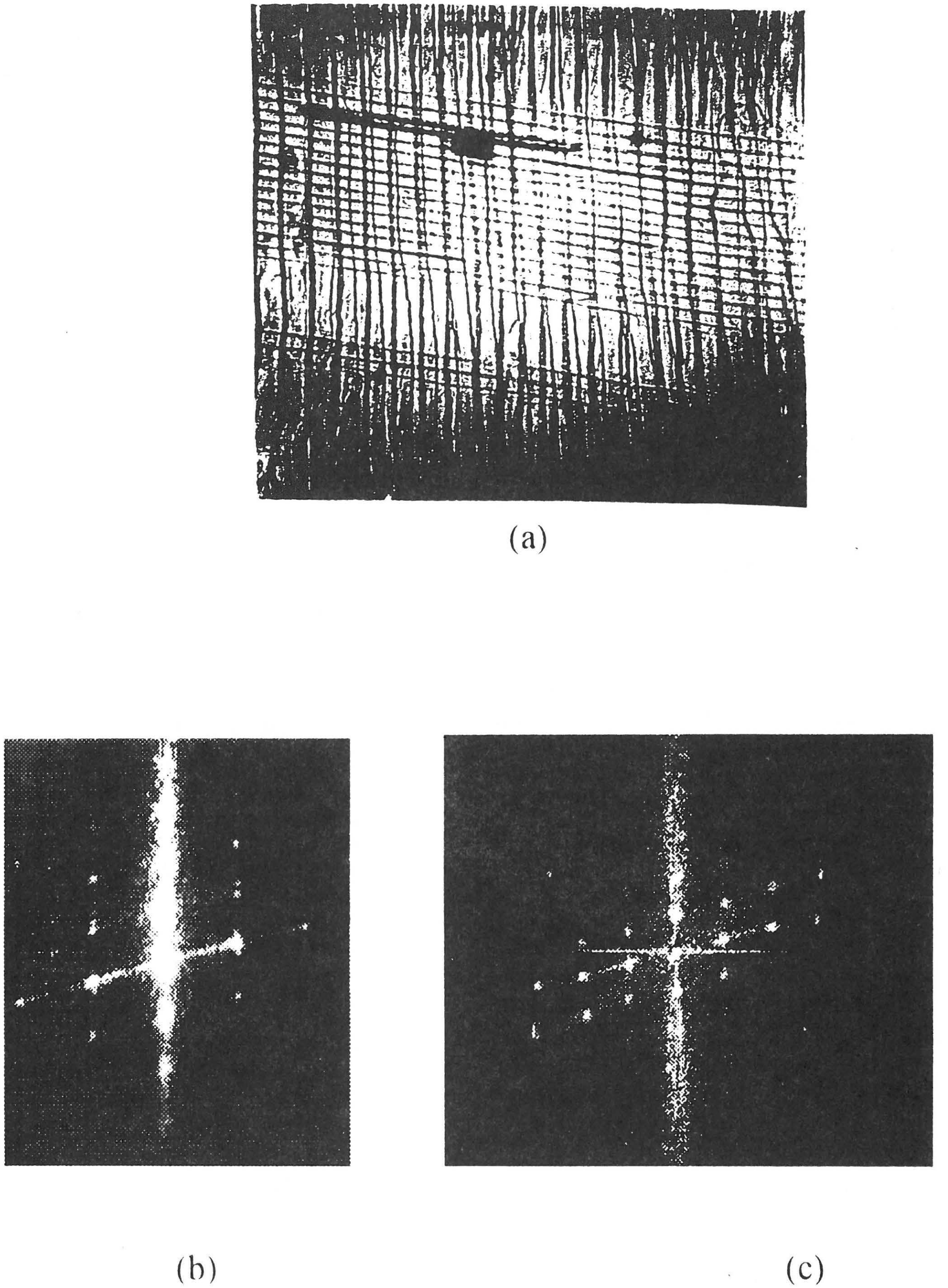


Fig. 6. Bidimensional periodic structures obtained from radial sections (a), experimental diffraction patterns (b) and diffraction patterns calculated using FFT (c).

Table 1. Calculated and measured mean values of transverse sizes of tracheids (d), obtained from samples of some species of softwood and hardwood. Estimated error, 5%

Species	Earlywood d (μm)		Latewood d (μm)	
	Calculated	Measured	Calculated	Measured
Picea abies	40	43	26	21
Cupressus sempervirens	27	23	19	16
Pinus nigra	42	39	28	24

the structure created when tracheids and medular rays cross (Fig. 6a), behaves as a bidimensional amplitude diffraction grating, generating diffraction patterns which can be easily interpreted (Fig. 6b). From these figures we can observe a pattern with some maxima of intensity, with the same structure that would correspond to a pattern obtained from a bidimensional diffraction grating. The distance between maxima allows the determination of the grating size, using Eq. (4).

Results are shown in Table 2, and can be interpreted as the physical dimensions of the structure generated when medular rays and tracheids cross.

Diffraction patterns obtained using the bidimensional FFT also agree with those obtained with the experiment (Fig. 6c).

Table 2. Mean values of the bidimensional sizes of periodic structures observed in radial sections. Estimated error, 5%

Species	Calculated (μm x μm)	Measured (μm x μm)
Picea abies	17 x 35	17 x 34
Cupressus sempervirens	16 x 25	18 x 25
Pinus nigra	21 x 39	20 x 42

CONCLUSIONS

The most important conclusion is that it is possible to use optical techniques to study the microscopic structure of wood with great accuracy.

On the other hand, Optical Image Processing (OIP) techniques enable the simulation of the Fourier Transform of a real sample. Analysis of these patterns lead to obtain results about the sizes of wood fibers which are very similar to those measured using an optical microscope.

Finally, it is possible to use optical techniques to determine the width and other features of tree-rings. From this knowledge, climatic information can then be obtained.

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