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ULTRASONIC INVESTIGATION OF FIBRE TEXTURE IN PLANTS

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The propagation velocities of an ultrasonic dilatational wave in different segments of a cereal stalk were measured and the averaged orientations of crystallites in the same segments were determined applying X-ray diffraction method. Using the principle of maximum entropy the analytical form of the probability density function of the crystallite orientation in a segment was found for the different values of the propagation velocity observed. Subsequently the fractions of crystallites with orientation angles lying in a given finite angle interval were calculated for the arbitrarily chosen propagation velocities.

1. Introduction

This work is a continuation of a series of papers [1-5] devoted to the microstructure and mechanical properties of the cereal stalk materials. Such information is very important for developments in breeding of plants, technology of harvest, textile and paper industries, and so on. The purpose of this paper is to present some experimental and theoretical investigations concerning the possibility of predicting the mechanical properties of the wheat stalk from ultrasonic measurements.

2. Formulation of the problems

It is obvious that the characteristic properties of the microstructure are the only reliable basis for the theoretical prediction of the mechanical properties of plant materials. For this reason the investigations presented here were carried out in two steps. The first step was to establish experimentally the relation between some characteristics of the local microstructure of the stalk and the local velocity of ultrasonic waves propagating in it as well as other mechanical properties of the stalk. The second step was an attempt to solve an inverse problem to the first one, that is to determine to some extent the local microstructure from measurements of the local propagation velocity of ultrasonic waves in the stalk. The inverse problem was solved on the basis of information theory. In this paper we are interested only in the material of the internodal parts of the stalk.

Seeking solutions for the effective mechanical properties of the plant material of a stalk segment lying between two neighbouring nodes, let us regard this material as a two-phase and fibre-reinforced one. In this approximation one phase is taken to be composed of circular cellulose fibres embedded in a continuous and amorphous phase, called the matrix phase. Generally speaking, the effective mechanical properties of such a medium depend on the fibre phase properties, the matrix phase properties and the volume concentration of each phase. On the basis of an analysis of such a model it can be expected that the effective mechanical behaviour of the plant material between two neighbouring nodes of the stalk is dominated by viscoelastic phenomena in the fibre phase with the volume concentration of about 70 per cent. For this reason we are interested only in the microstructure of the fibres.

In the cellulose fibres there form crystalline areas called micelles or crystallites separated from one another, along the fibre, by amorphous areas of lesser degree of particle ordering. Let θ denote the orientation of a crystallite in relation to the axis of the fibre, that is θ denotes the angle between the axis of the crystallite and the axis of the whole fibre. Let $p(\theta)d\theta$ denote the probability that the orientation angle of an arbitrarily chosen crystallite has a value between θ and $\theta+d\theta$. The probability density function $p(\theta)$ introduced here describes the so-called texture of the plant material. It should be stressed here that the mechanical, acoustical, sorbtion and some other properties of the stalk material are determined mainly by the texture. For this reason the texture was the only parameter of the stalk microstructure of interest for us.

3. Experiments and analysis

In order to determine the orientation angle $\bar{\theta}$ averaged over all the crystallites in different internodal parts of the stalk, segments were taken from different internodal parts lying along the whole length of the dried stalk. A macroscopic sample in the form of a rod with the longitudinal axis parallel to that of the stalk was cut off from each segment.

These samples were first investigated using X-ray diffraction. A Debye-Scharer camera using radiation from a copper lamp with a nickel filter was employed. These observations permitted quantitative measurements of the mean orientation angle $\bar{\theta}$.

Subsequently the values of the propagation velocity of ultrasonic dilatational waves, c_L, were determined for 1 MHz waves propagating in the samples along their longitudinal axes. The propagation velocity was determined for each sample from the measurement of the time of the passage of an ultrasonic impulse between two points of some distance between them. The thickness, d, of each sample was several times smaller than the wave length, λ, and the conditions

$$d/\lambda < 0.3, \qquad \lambda/l \ll 1 \tag{3.1}$$

were fulfilled, where l denotes the sample length. Under these conditions the effective dynamic Young's modulus, $E(\omega)_{\text{eff}}$ and the propagation velocity, $c(\omega)_L$, are related to each other by the following relationship

$$E(\omega)_{\text{eff}} = \langle \varrho \rangle [c(\omega)_L]^2, \tag{3.2}$$

where ω denotes the angular frequency of the ultrasonic wave and the angular brackets $\langle ... \rangle$ denote averaging over the sample volume. This formula enables us to determine the values of the dynamic effective Young's modulus of plant material from measurements of the propagation velocity of the dilatational ultrasonic wave. The respective curve in Fig. 1 shows how the mean orienta-

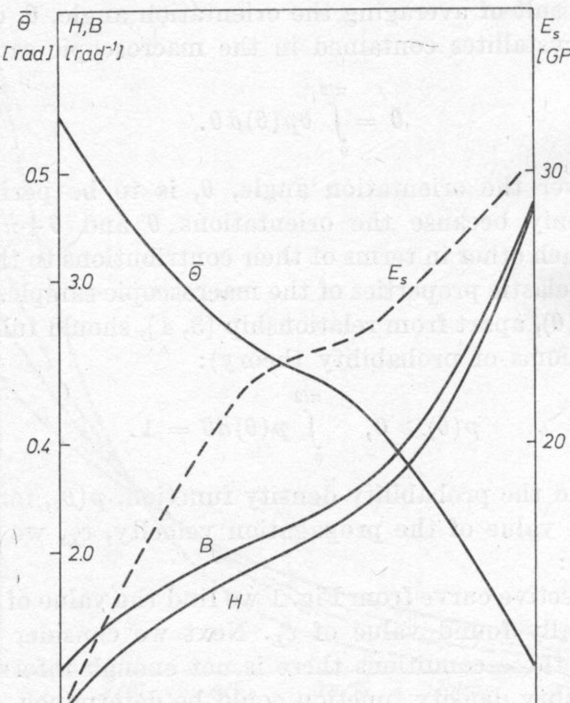


Fig. 1. Changes in the mechanical properties of the stalk material produced by changes in the texture of the stalk fibres

tion angle, $\bar{\theta}$, and the propagation velocity, c_L, are related to each other. The relationship between $\bar{\theta}$ and c_L can be expressed, for example, in the following form

$$\bar{\theta} = \sum_{k=0}^{6} A_k^{(\theta)} (c_L)^k, \quad [A_k^{(\theta)}] = [m^{-k} s^k]. \tag{3.3}$$

The numerical values of the coefficients $A_k^{(\theta)} (k = 0, 1, \ldots, 6)$ are listed in the first column of Table 1. On the other hand, the mean orientation, $\bar{\theta}$, can

Table 1

k	$A_k^{(\theta)}$	$A_k^{(H)}$	$A_k^{(B)}$
0	-13367.5	-67850.06	131496.8
1	17.806	83.428	-166.21048
2	$-9.84866.10^{-3}$	-0.04246	0.08725
3	$2.899574 \cdot 10^{-6}$	$1.114506 \cdot 10^{-5}$	$-2.4347 \cdot 10^{-5}$
4	$-4.79275 \cdot 10^{-10}$	$-1.72504 \cdot 10^{-9}$	$3.80983 \cdot 10^{-9}$
5	$4.21707 \cdot 10^{-14}$	$1.37638 \cdot 10^{-13}$	$-3.169755 \cdot 10^{-13}$
6	$-1.543134 \cdot 10^{-18}$	$-4.54343 \cdot 10^{-18}$	$1.0956 \cdot 10^{-17}$

be regarded as a result of averaging the orientation angle, θ, over a statistical ensemble of the crystallites contained in the macroscopic sample, i.e.,

$$\bar{\theta} = \int_0^{\pi/2} \theta p(\theta) d\theta. \tag{3.4}$$

Integration over the orientation angle, θ, is to be performed over the interval $[\theta, \pi/2]$ only because the orientations θ and $\theta + \pi/2$ $(0 \leqslant \theta \leqslant \pi/2)$ are equivalent to each other in terms of their contributions to the determination of the longitudinal elastic properties of the macroscopic sample. The probability density function $p(\theta)$, apart from relationship [3, 4], should fulfill the following two conditions (axioms of probability theory):

$$p(\theta) \geqslant 0, \quad \int_0^{\pi/2} p(\theta) d\theta = 1. \tag{3.5}$$

In order to find the probability density function, $p(\theta)$, for a given sample from the measured value of the propagation velocity, c_L, we may proceed in the following way:

Using the respective curve from Fig. 1 we find the value of $\bar{\theta}$ corresponding to the experimentally found value of c_L. Next we consider conditions (3.4) and (3.5). Since in these conditions there is not enough information available so that the probability density function could be determined, we make use of the information theory method like in [6]. Accordingly, in order to make statistical inferences from partial information, we must find this probability density function which has maximum Shannon entropy and is subject to whatever is known [7], i.e., subject to constraints (3.4), (3.5). From this, it follows that the probability density function, $p(\theta)$, should be taken in the following form:

$$p(\theta) = B(c_L)\exp[-H(c_L)\theta], \qquad B = H/[1-\exp(-\pi H/2)]. \tag{3.6}$$

The functional relationships $H = H(c_L)$ and $B = B(c_L)$ can be expressed, for example, in the following form:

$$H = \sum_{k=0}^{6} A_k^{(H)}(c_L)^k, \quad B = \sum_{k=0}^{6} A_k^{(B)}(c_L)^k, \qquad [A_k^{(H)}] = [A_k^{(B)}] = [\mathrm{rad}^{-1} m^{-k} s^k]. \tag{3.7}$$

The numerical values of the coefficients $A_k^{(H)}$ and and $A_k^{(B)}$, corresponding to the experimental relationship (3.3), are listed in the second and third column of Table 1, respectively. The respective curves in Fig. 1 show how H and B depend on the propagation velocity.

Making use of these results we can plot the probability density function, $p(\theta)$, corresponding to all reasonable values of the propagation velocity c_L. Fig. 2 presents four curves of four probability density functions corresponding

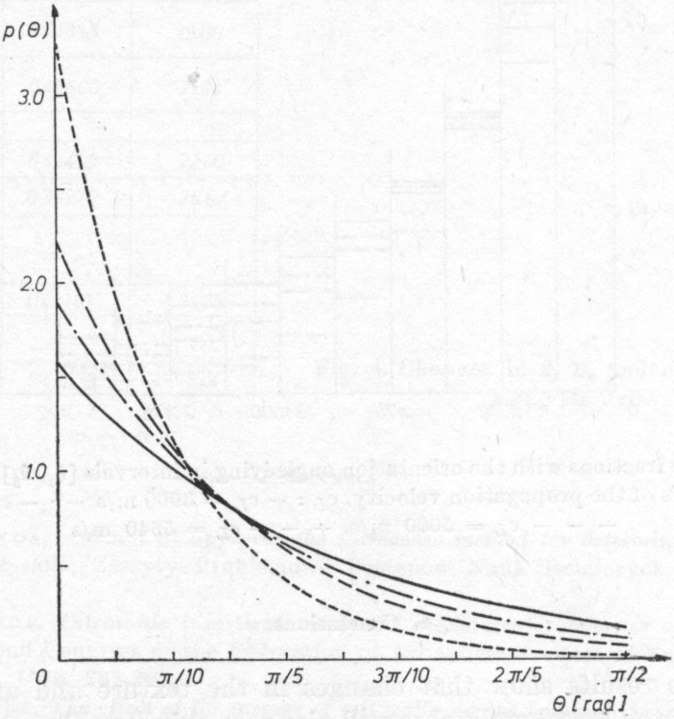


Fig. 2. Probability density functions, $p(\theta)$, corresponding to different values of the propagation velocity, c_L : — $c_L = 3900$ m/s, — · — $c_L = 4340$ m/s, – – – $c_L = 5000$ m/s, — — — $c_L = 5640$ m/s

to the four different values of the propagation velocity. The angle between the vertical axis and the tangent of the curve $p(\theta)$ can be regarded as a measure of isotropy. The anisotropy of the material considered increases as this angle decreases. From changes in this slope, it can easily be seen that the propagation velocity, c_L, observed along the stalk axis diminishes with decreasing the longitudinal anisotropy of the stalk material.

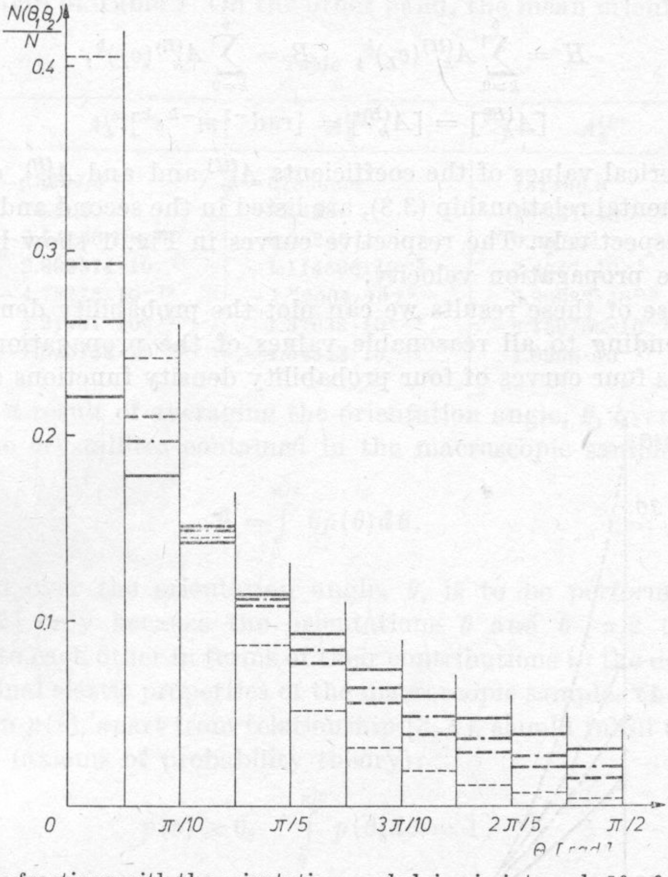
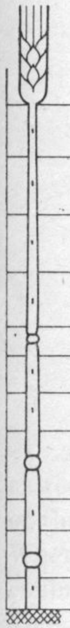


Fig. 3. Crystallite fractions with the orientation angle lying in intervals $[\theta_1, \theta_2]$ corresponding to different values of the propagation velocity, c_L : $-$ $c_L = 3900$ m/s $- \cdot -$ $c_L = 4340$ m/s, $- - -$ $c_L = 5000$ m/s, $- - -$ $c_L = 5640$ m/s

4. Conclusions

The above results show that changes in the texture and anisotropy of the material of the cereal stalk observed along its axis over the whole distance between the root and ear cause changes in the propagation velocity, c_L, and are expected to produce essential changes in all the mechanical properties of the material. Of course, these changes can be measured or observed by suitable techniques. For example, results obtained by sample stretching on the Instron testing machine indicate such a great differentiation in the properties of material of the stalk along its axis. For internodal segments in which ultrasonic waves propagate with a high velocity, 4000-5600 m/s, linear stress-strain characteristics occur for axial stresses until the sample rupture which is dominated in this case by the phenomenon of brittle fracture. Conversely, for those internodal segments below the ear in which the wave velocity is about 3000 m/s, stress-strain characteristics for axial stresses are similar to the characteristics of plastics materials. Fig. 4 presents the changes in $\bar{\theta}$, c_L and the effective Young's modulus, E_s, obtained by sample stretching on the Instron testing machine. The values of this modulus are also plotted in Fig. 1.



$c\,[ms^{-1}]$	$\bar{\theta}\,[rad]$	$E_s\,[GPa]$
2763		
3899	0.52011	17.00
4423	0.44855	19.00
4345	0.46600	21.04
4762	0.43459	22.40
5200	0.39270	26.63
4863	0.43110	24.25
4261	0.43633	18.44

Fig. 4. Changes in $\bar{\theta}$, E_s and c_L in the stalk along its axis

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