DEPENDENCE OF ACOUSTICAL CHARACTERISTICS ON MOLECULAR ORIENTATION
AND STRENGTH OF MAN-MADE FIBRES

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In recent years we have developed methods of simultaneously determining the velocity of propagation and absorption of longitudinal ultrasonic waves in man-made fibres and textile yarns [1]. A simultaneous analysis of the change in these characteristics makes it possible to obtain broad information about the structure of man-made fibres and yarns and the relaxation processes which take place in them. For many types of yarns, an interconnection has been detected between the damping coefficient and the rate of propagation of ultrasonic waves, C(α). A similar relationship is observed for yarns of any chemical nature or geometric structure, and does not depend on many parameters in their preparation and testing.

In the present communication we describe the application of this dependence for a wide class of yarns, and we make an attempt to interpret physically the C(α) connection and to establish the correlation of acoustical parameters with the orientation of macromolecules and the strength of various man-made fibres.

The objects of investigation were the following: polycaproamide (PCA), polyethylene (PE), and polyvinyl alcohol (PVA) technical yarns and monofilaments with various orientation stretch ratios; viscose yarns prepared under various spinning conditions; and ultrahigh modulus fibres which had been heat-treated in various ways.

The propagation velocity and quenching coefficient of ultrasonic waves were determined by the pulse method, using a two-base measurement under normal climatic conditions [1].

In Fig. 1 we give generalized data on the propagation rate of sound and the damping coefficient of ultrasonic waves for various man-made yarns. Change in these characteristics was achieved by orientation stretch of the yarns from flexible-chain polymers and by changing the heat-treatment conditions for ultrahigh modulus yarns.

Attention is drawn to the fact noted previously by the authors for PCA and viscose yarns: An increase in the degree of orientation of the macromolecules is always accompanied by a decrease in the damping coefficient of ultrasonic waves. Since this relationship has been detected for yarns of various chemical natures (PCA, PE, PVA, viscose, and yarns based on aromatic polyamides), there is a basis for considering it rather general and for assuming that this dependence will also be obeyed by other polymers not described in this article.

There is no single opinion about the physical mechanism for the interconnection between the rate of propagation of sound and the absorption of ultrasonic waves. As is well known [2], the rate of sound propagation C and the coefficient of absorption of ultrasonic waves, α, are connected with the modulus of elasticity, E', and the loss modulus, E'', by the following relationships:

\[ E' = \frac{\rho C^2 [1 - \left(\frac{\alpha \lambda}{2\pi}\right)^2]}{[1 + \left(\frac{\alpha \lambda}{2\pi}\right)^2]} \]
\[ E'' = \frac{2\rho C^2 \frac{\alpha \lambda}{2\pi}}{[1 + \left(\frac{\alpha \lambda}{2\pi}\right)^2]} \]

For the case of weak damping, \( \alpha \lambda \ll 1 \), we have

\[ E' = \rho C^2; \quad E'' = \frac{\rho C^2 \frac{\alpha \lambda}{\pi}}{\pi}; \quad \tan \delta = \frac{\alpha \lambda}{\pi} \]

or, for constant test conditions (\( \rho = \text{const}; \quad \lambda = \text{const} \))

\[ \alpha = \text{const} \left(\frac{E''}{C^2}\right) = \text{const} \tan \delta \]

where \( \rho \) is the density of the material; \( \lambda \) is the wavelength; and \( \tan \phi \) is the mechanical loss tangent.

In conformity with the concepts developed by Zabashta [3], a dependence between \( C \) and \( \alpha \) can be obtained by using the well known dispersion relationship of [4, p. 82], which relates the values of \( C \) and \( \alpha \) with the components \( I' \) and \( I'' \) of complex compliance.

To establish the form of \( C(\alpha) \), one can use the model of nonidentical relaxers which was developed for oriented crystallizing polymers (by relaxer, we are to understand some kinetic unit which is able to become oriented variously under the action of a force field) [3,5]. For this model, the following relationships hold true:

\[
I' = I_0 + \int_{U_o}^{\infty} \int_{0}^{\infty} \frac{f(V)}{1 + \omega^2 \tau^2} \Phi(U, V) \, dU \, dV
\]

\[
I'' = \int_{U_o}^{\infty} \int_{0}^{\infty} \frac{f(V) \omega}{1 + \omega^2 \tau^2} \Phi(U, V) \, dU \, dV
\]

\[
I'(V) = \frac{N \langle \varepsilon^2 \rangle}{T} \exp \left( -\frac{V}{T} \right) \left[ 1 + \exp \left( -\frac{V}{T} \right) \right]^{-2}
\]

\[
\tau = \tau_0 \exp \frac{U - V}{T}
\]

where \( N \) is the relaxer concentration; \( T \) is temperature; \( \tau \) is relaxation time; \( V \) is the difference in energy levels of a relaxer; \( U \) is the energy barrier; \( \tau_0, \langle \varepsilon^2 \rangle \) are relaxer parameters; and \( \omega \) is frequency.

The model examined is correct in the case where \( (U - V) \gg T; \ U \gg T \). Then \( V \ll U \), and Eq. (7) acquires the form

\[
\tau = \tau_0 \exp \left( \frac{U}{T} \right).
\]

In the case where \( \omega \tau \gg 1 \), instead of Eqs. (1) and (2), one can write

\[
I' = I_0 + \frac{1}{\omega^2} \int_{U_o}^{\infty} \int_{0}^{\infty} \frac{f(V) \Phi(U, V)}{\tau^2} \, dU \, dV
\]

\[
I'' = \frac{1}{\omega} \int_{U_o}^{\infty} \int_{0}^{\infty} \frac{f(V) \Phi(U, V)}{\tau} \, dU \, dV
\]

By virtue of the inequality \( U \gg T \), the function \( \tau^{-1}(U) \) is a rapidly diminishing one. Since \( \Phi(U, V) \) changes far more slowly with respect to \( U \), we arrive at the following result:

\[
\int_{U_o}^{\infty} \frac{\Phi(U, V) \, dU}{\tau^2} = \frac{T \Phi(U_o, V)}{\tau_0} \exp \left( -\frac{U_o}{T} \right) = \frac{T \Phi(U_o, V)}{\tau(U_o)}
\]

\[
\int_{U_o}^{\infty} \frac{\Phi(U, V) \, dU}{\tau^2} = \frac{T \Phi(U_o, V)}{2\tau_0} \exp \left( -\frac{2U_o}{T} \right) = \frac{T \Phi(U_o, V)}{2\tau^2}
\]

Therefore Eqs. (4) and (5) acquire the form

\[
I' = I_0 + \frac{G}{2\omega^2 \tau^2 (U_o)}
\]