Influence of inclination angle of piezoelectric receiver of ultrasonic sensor on the error in measurement of the average fiber diameter

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Abstract. During experimental studies, an ultrasonic device was used which in terms of design ensured maximum acoustic pressure on the receiving element, minimized the effect of external disturbances (environmental condition parameters) on the measurement result; decreased spatial variations of the source and receiver of ultrasonic waves during measurement, optimized the design and spatial positioning of ultrasonic vibration receiver.

The measuring channel settings accepted during experimental studies are as following: \( a_k \) – design constant of measuring channel; \( a_k = 14 \), where \( a \) is half-width of the channel, \( a = 5 \, \text{mm} \); \( k \) – wave number, \( k = 2.8 \). Experimental evaluation had confirmed theoretically substantiated effect of inclination angle of the receiving element of the ultrasonic sensor on the error in measurement of wool fineness in a disarrayed sample. At the inclination angle of the ultrasonic sensor receiver of \( \beta = 48^\circ \) relative to the longitudinal axis of the measuring channel, the error does not exceed \( \pm 1.5\% \), and at the angle of \( \beta = 0^\circ \) it does not exceed \( \pm 5\% \).

The reason for more accurate measurement of wool fineness at \( \beta = 48^\circ \) in accordance with the developed theoretical provisions is that the inclination of the receiving piezoelectric element of the sensor relative to the longitudinal axis of the measuring channel eliminates the need for receiver installation at the angle of \( \beta = 0^\circ \) strictly in so-called ultrasonic wave antinode, which poses a significant technical problem at ultrasonic wave frequency of 150 kHz. Besides, the receiver arrangement at inclination relative to the longitudinal axis of the measuring channel allows increasing the spots of contact of ultrasonic wave with the surface of the receiving element irrespective of wave phase, and increases the average acoustic pressure and decreases the measurement error.

Checking of fiber diameter of synthetic and organic nature in a continuous process for the production of artificial, synthetic, natural fibers and cords is an actual scientific and technical problem.

Yarns and fibers, located in the disarrayed sample, represent a special class of objects, characterized by a significant anisotropy of physical properties.

In the case, when the method and technical means measurement of the fiber diameter allows to obtain the fiber diameter value in a disarrayed sample with the required error, the sensor is able to estimate the fiber diameter with the required assurance in other conditions.

A disarrayed sample of sheep wool was selected as an universal object of research (physical generalized model). In this case, the revealed regularities can be extended to the processes of assessing the fibers diameter of a different physical nature subject taking into account certain restrictions.

This work continues the researches started by the authors in papers [1-5] and is associated with the development of methods and the improvement of technical means of wool fineness measurement of fibers in a disarrayed (irregular) sample.
The result of the theoretical studies is the following hypothesis: inclination angle of the receiving piezoelectric element of the ultrasonic sensor effects on the error in measurement of the average fibers diameter in a disarrayed sample.

It should be borne in mind a number of preset conditions. The maximum average pressure remains constant in a wide range of variation of the setting \( a k = (7...25) \), where \( a \) is the half-width of the acoustic channel, mm; \( k=2\pi f/c \) - wave number; \( f \) – ultrasonic wave frequency (\( f= 150 \) kHz); \( c \) – sound speed. In particular, when \( a k =14 \) the inclination angle of acoustic vibrations receiver is \( \approx 48^0 \), and the half-width of the channel \( a=5 \) mm. The geometric parameters of the acoustic channel for a given frequency can be determined for other values of the coefficient \( a k \). The specified frequency of the ultrasonic wave, the inclination angle of the receiver and the half-width of the channel are used in the sensor design.

The hypothesis of the influence of inclination angle of the receiving piezoelectric element of the ultrasonic sensor on the measurement of the average wool fineness requires empirical support.

The aim of this work is the experimental evaluation of the effect of inclination angle of the receiving element of the ultrasonic sensor on the error in measurement of the average fiber diameter in a disarrayed wool sample.

The task of the study is to conduct experimental studies, mathematical processing and interpretation of the measurement of the average wool fibers diameter at the inclination angles of the receiving element of the sensor \( \beta =0^0 \) and \( \beta =48^0 \).

1. Experimental installation

Figure 1 shows the structure-functional scheme of the device for ultrasonic express control of the average wool fibers diameter. The scheme contains a reference frequency generator 1, an integrating amplifier 2, a piezoelectric emitter 3, acoustic vibration receivers 4 and 5, a standard wool sample with a known fiber diameter 11, a sample of test fiber material 12, amplifiers 6 and 9, a reference signal source 7, an AGC signal conditioner 8, recording device 10.

The main elements of the device are the sensors (blocks 1,2,3,4) and the registering device 10. The device is characterized by measuring (blocks 4,9,10) and reference (blocks 5,6,7,8) channels.

Acoustic vibrations in the measuring channel of the sensor are attenuated as a function of the fiber material settings 12 and converted in the receiver 4 into electrical signals, which are amplified in block 9 and are fed to the input of the digital recorder 10.

In the reference channel (blocks 5-8) acoustic vibrations varying in amplitude and phase under the environment condition are perceived by the receiver 5, converted by the amplifier 6 and fed to the input of the unit phase-locked loop 8 and adjusted by the signal generator 2 to compensate for the influence of external disturbances. Thus, a constant intensity of acoustic vibration emission in the sensor channel is kept. This allows to exclude the influence of such environmental factors as temperature, atmospheric pressure, humidity and gas composition on the measurement result.

The sensor shown in Figure 2 contains a split housing 1, into which the emitter 2, receiver 3 and additional receiver of the reference channel 4 are embedded.
Emitter 2 is a piezoelectric transducer of two-way emission. The receiver 3 is made as a one-sided piezoelectric transducer. Measuring 6 and reference channels 5 connect the emitter 2 and receiver 3 and an additional receiver 4.

The piezoelectric ceramics of the lead zirconate-titanate type -19 is used as a material of the source and transducer receiver.

The emitter design has been developed (Figure 3) to increase the temperature stability and spatial stabilization of the emitter and the receiver. A distinctive feature of the design is the fixation of the piezoelectric element 1 in the foam rubber housing 2, which improves the accuracy of the installation of the piezoelectric elements source and receiver relative to the longitudinal axis of the sensor, reduces the oscillation of the device during operation, expands the region of resonant frequencies and increases the temperature stability of the emitter, improves the piezoelectric elements alignment.

An acoustically transparent tray-holder (Figure 4) was developed to fix the test material sample. It allows to research the sample with acoustic waves from four sides, which gives an average attenuation independent of the fibers distribution in the sample.

Figure 5 shows the external view of the device for express-control of the average diameter of the fiber material.

2. Research methodology

The authors have proposed a method for determining the average fiber diameter in a disarrayed sample [8], which consists in the researching of the test material sample by an ultrasonic wave with simultaneous measurement of the amplitude of acoustic vibrations transmitted through the sample. It is
distinguished by the fact that, in order to increase the accuracy, the sample is subjected to a compressive load, placed into an acoustically transparent holder (see Figure 4), kept up to complete relaxation of the elastic component, placed into the measuring channel of the sensor (see Figure 2) and sequentially researched with acoustic waves from four longitudinal edges of the sample perpendicular to the compression. The sample fiber diameter is calculated as the arithmetic average found from the results of measuring the amplitudes of the ultrasonic wave along the four sample faces.

The method is implemented as follows. The device (Figure 5) is switched on to the network, heated for 10 minutes, and the zero point is set by the control hinge of the fibers.

A standard sample with a known average fibers diameter with a mass of 0.2 g is placed into the holder tray (see Figure 4), maintained until the relaxation state and placed into the reference channel 5 of the device (see Figure 2).

The test sample is treated in the same way, but it is put into the channel 6 of the ultrasonic sensor (see Figure 2).

Passed through the sample an acoustic signal is fixed. The measurement results are displayed; automatically recording on electronic media is possible.

Then the fiber holder with the test sample is removed from channel 6 and researched with acoustic waves from the side of the three remaining faces, consistently turning. At the same time rates of acoustic attenuation are fixed at a constant level of the emitter signal. The average fiber diameter is calculated as the arithmetic average of four measurements.

Main content pre-processing of measurement results is to check the normality of the distribution.

2. Processing methods of measurement results

It is known [9], that the main content of preliminary measurement results is to test the normality of distribution with the evaluation of such sample characteristics as the average value of the observable characteristic \( \bar{x} \) and standard deviation \( S \).

The Distribution of errors of measurement result in most cases submits to the normal law of the Gaussian distribution [10]. For small samples (\( n<120 \)) is known [11] a simple check of normality of distribution associated with the calculation of the average absolute deviation (CAO).

\[
CAO = \frac{\sum |x_i - \bar{x}|}{n} \tag{1}
\]

For the sample \( n=10 \) with a normal distribution should occur the following condition

\[
\left| \frac{CAO - 0.7979}{S} \right| < \frac{0.4}{\sqrt{n}} = 0.12 \tag{2}\]

Confidence interval for true value of fineness \( a \) [12]

\[
\bar{x} - \frac{t_\alpha S}{\sqrt{n}} < a < \bar{x} + \frac{t_\alpha S}{\sqrt{n}} \tag{3}\]

where \( t_\alpha \) is the limiting value. For the probability \( a = (1-P) / 2 = 0.005 \), the accepted sample is \( n = 10 \) and the number of degrees of freedom is \( k = n-1 = 9 \), the limit is \( t_\alpha = 3.25 \) [12].

Confidence limit for the variance \( S^2 \) [12]

\[
\frac{(n-1)S^2}{X_{\alpha_1}^2} < S^2 < \frac{(n-1)S^2}{X_{\alpha_2}^2} \tag{4}\]

where \( \alpha_1, \alpha_2 \) are probabilities, for a confidence level 0.95 \( \alpha_1 = (1-0.95)/2 = 0.025 \), \( \alpha_2 = 1-(1-0.95)/2 = 0.975 \); \( X_{\alpha_1}^2 \), \( X_{\alpha_2}^2 \) - values of the upper and lower limits of the interval, respectively, for the number of degrees of freedom \( k=n-1=9 \); \( X_{\alpha_1}^2 = 19.023 \), \( X_{\alpha_2}^2 = 2.7 \) [12].

The absolute \( \Delta \), \( \mu \), and relative \( \delta \), \( % \), errors are determined by known methods [10,12]. Merino wool with a fiber diameter of 19.84 \( \mu \)m, defined in accordance with GOST 17514-93 is used as a standard or measure.

3. Results and discussion

Table 1 shows the results of statistical processing of 10 samples using the above method with the inclination angle of the receiving element of the ultrasonic sensor of \( \beta = 0^\circ \) and \( \beta = 48^\circ \) relative to the longitudinal axis of the measuring channel.
Table 1. Preliminary processing results of n-measurements of the average wool fineness in a disarrayed wool sample at different inclination angles of piezoelectric receiver $\alpha$.

| $\bar{x}$, $\mu$m | $\sum (x_i - \bar{x})$ | $\sum (x_i - \bar{x})^2$ | $S^2$ | $S$ | CAO, $\mu$m | $\frac{CAO}{S} - 0.7979$ |
|-------------------|------------------------|--------------------------|--------|-----|-----------|-------------------|
| $\beta = 0^\circ$ | 20.805                 | 8.8                      | 10.126 | 1.01 | 0.885     | 0.087             |
| $\beta = 48^\circ$| 20.055                 | 6.57                     | 5.173  | 0.517| 0.719     | 0.657             |

Analysis of table 1 using condition (2) allows for the following conclusion: the hypothesis of the normal distribution of the data sample is confirmed in both cases.

Table 2 presents the results of estimating the confidence intervals of the fiber diameter $a$, the standard deviation $S$, the absolute $\Delta$, and the relative $\delta$ errors at different inclination angles of the piezoelectric receiver, $\beta$. The analysis shows that the mathematical expectation of the fiber diameter, found as an arithmetic average of the measurement results on 4 faces, when the receiving element of the sensor is at an angle $\beta = 48^\circ$, is closest to the reference value compared to the angle $\beta = 0^\circ$; at the inclination angle $\beta = 48^\circ$, the error does not exceed $\pm 1.5\%$, and at the angle $\beta = 0^\circ - \pm 5\%$.

Table 2. Results of evaluation of confidence intervals of fiber diameter $a$, standard deviation $S$, absolute $\Delta$ and relative $\delta$ errors at different inclination angles of the piezoelectric receiver $\beta$ ($n = 10$).

| confidence | $\chi^2_a$ | $\chi^2_S$ | interval for $S$ | $\Delta$, $\mu$m | $\delta$, $\%$ |
| interval for $a$, $\mu$m | | | | |
| $\beta = 0^\circ$ | 20.805±1.08 | 19.023 | 2.7 | 0.69 $\leq S < 1.98$ | 0.965 | ±5 |
| $\beta = 48^\circ$ | 20.055±0.778 | 19.023 | 2.7 | 0.49 $\leq S < 1.313$ | 0.215 | ±1.5 |

The reason for more accurate measurement of fiber diameter at $\beta = 48^\circ$ in accordance with the developed theoretical provisions is that the inclination of the receiving piezoelectric element of the sensor relative to the longitudinal axis of the measuring channel eliminates the need for receiver installation at the angle of $\beta = 0^\circ$ strictly in so-called ultrasonic wave antinode, which poses a significant technical problem at ultrasonic wave frequency of 150 kHz. Besides, the receiver arrangement at angle allows increasing the spots of contact of ultrasonic wave with the surface of the receiving element irrespective of wave phase, and increases the average acoustic pressure and decreases the measurement error. The obtained results are in qualitative agreement with the scientifical attitude outlined in the works [13, 14]. At the same time, the analytical and experimental base proposed by the authors makes it possible to increase the accuracy in measuring of average fiber diameter on the basis of previously unknown revealed regularities.

4. Conclusions. The measuring channel settings accepted during experimental studies are as following: $ak = 14$, where $a$ - is half-width of the channel, $a = 5$ mm; $f$ - ultrasonic wave frequency, $f = 150$ kHz; $k$ - wave number, $k = 2\pi f/c$, $c$ - sound speed. Experimental evaluation had confirmed theoretically substantiated effect of inclination angle of the receiving element of the ultrasonic sensor on the error in measurement of average fiber diameter in a disarrayed sample. At the inclination angle of the ultrasonic sensor receiver of $\beta = 48^\circ$ relative to the longitudinal axis of the measuring channel, the error does not exceed $\pm 1.5\%$, and at the angle of $\beta = 0^\circ$ it does not exceed $\pm 5\%$.

The established regularities make it possible to extend the results of the present studies to the processes of determining the fibers diameter in a disarrayed sample of materials of a different physical nature and geometric orientation in space. The main provisions of the theory of similarity are analytical and experimental base for further research are.
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