AUTOMATED SYSTEM FOR QUICK ULTRASONIC TRANSDUCERS CALIBRATION

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Introduction

Transducers calibration system AUGUR 5.4 which was developed in Scientific and Production Center "ECHO+" is a new generation of systems for probes verification [1, 2]. The system allows measuring or calculating most part of contact and immersion probes parameters described in European Standard EN 12688-2 and Russian Standards GOST 23702-90, GOST 14782-86. System's description and technical parameters, probes verification methodology presented at [3, 4].

One system is working from 2007 on Vyksa Steel Works to complete codes EN 12688-2 and DNV OS-F101 of probes calibration routine in international project NordStream. Batch of 10 systems was manufactured for Russian Railways. One system is working in Scientific and training center "Welding and testing".

The system is simple and compact. Main system feature is based on use of scanning device with one or two axes and single hemispherical or semicylinder test block (for contact probes) and small ball-type reflectors (for immersion probes). Single measurement with pulse-echo technique allows calculating of pulse parameters (pulse shape, pulse spectrum, sensitivity, noise level), probe index, beam axis offset, beam and squint angle, angles of divergence. The principle of full 3D directivity pattern calculation (therefore beam and divergence angles in any plane) based on calculation of multiple-frequency holograms of "omnidirectional source" (FT-SAFT framework). Distance-amplitude curves calculated numerically with discrete model of probe's crystal and batch of flat bottom reflectors. With acoustic holography framework the probe field could be calculated and visualized right up to probe plate. This allows to analyze beam properties and to seek flaws of probe plate.

The time for common parameters set verification (impulse parameters, sensitivity, probe index and directivity pattern in plane of incidence, noise curve, DAC) could be comlpeted for about a two minutes including probe set up, measurements, calculation and datasheet printing. Verification of full parameters set with 2D scanning and manual analysis of some characteristics could be completed for twenty minutes or less.

The paper describes experience of system application for verification of probes used in railway ultrasonic inspection. Enhancement of system construction, algorithms and techniques described. The errors of most probe parameters measurement were determined. Some influence functions were investigated. The R&R analysis was evaluated.
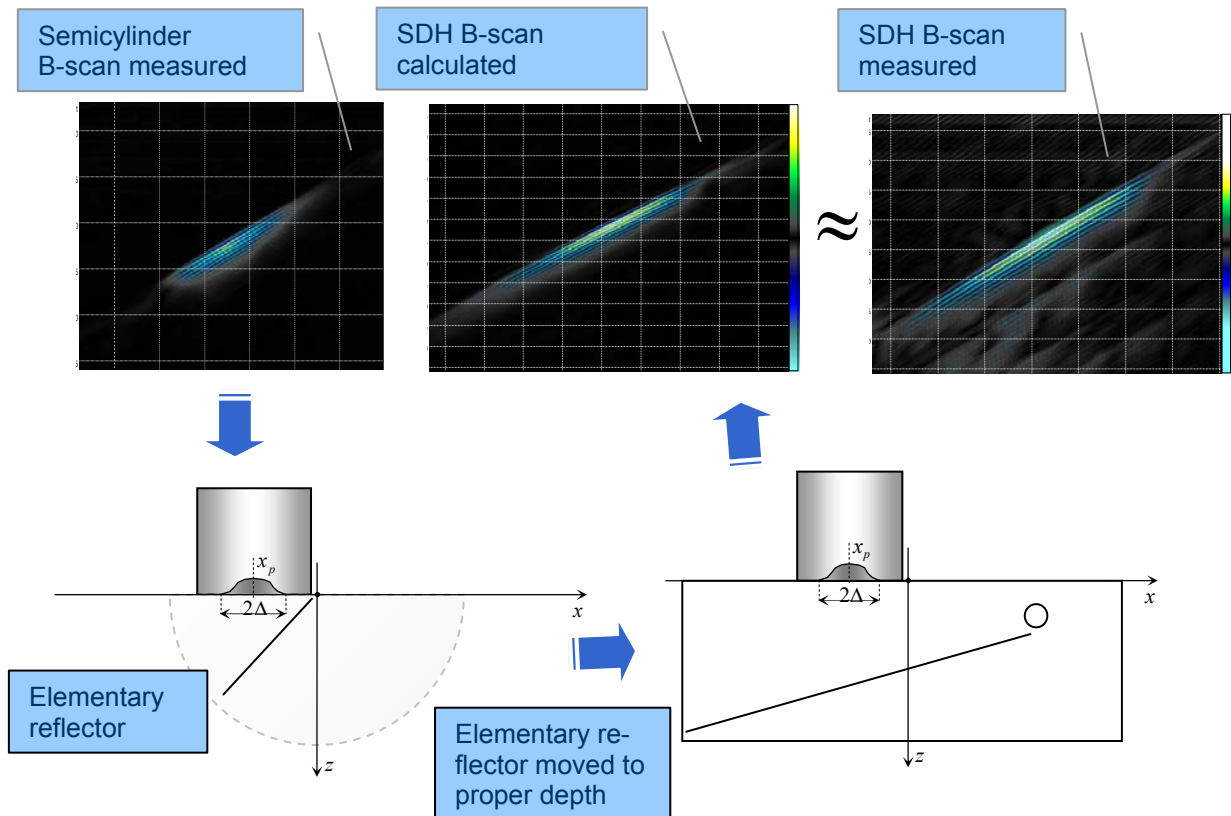
Application with Russian Railways

During system probation at Railroad track Department some modification in system construction were completed – just one scanning axis kept, new probe holders were developed. One can see common system view at Fig. 1.

New technique of beam angle calculation was developed. It uses the measurement of B-scan from semicylinder surface of reference block SO-3 which traditionally used for probe index measurement. This algorithm allows to obtain result of beam angle measurement similar to measurement using SDH but with rather simpler procedure. The algorithm based on acoustic holography framework and some explanations one can see at Fig. 2. The semicylinder ultrasonic field acquisition is equivalent to measurement of elementary reflector in the center of symmetry field. Then with use of angular spectrum method [5] the field is transferring to proper virtual SDH depth. Thus B-scan which is similar to B-scan with real SDH could be obtained. Directivity pattern and beam angle could be then calculated.

Fig. 1. Common view of AUGUR 5.4 system with single axis scanning device.

Semicylinder B-scan measured

SDH B-scan calculated

SDH B-scan measured

x_p

2Δ

x

z

Elementary reflector

Elementary reflector moved to proper depth

x_p

2Δ

x

z

Fig. 2. Scheme of B-scan from SDH calculation with use of elementary reflector in geometrical focus of semicylinder

Trueness of this technique was verified. Thirteen typical probes for rails inspect with various beam angles were verified by common hand-held routine with SDH and automated procedure with semicylinder. All measurements repeated five times. The bias was not over measurement error. The standard deviation of hand-held procedure was 0.55 degree and for automated procedure 0.31 degree. At Fig. 3 the comparison of two methods presented. One can see nominal beam angle value of each probe, ±2° tolerance, hand-held SDH and automated semicylinder measurement results.
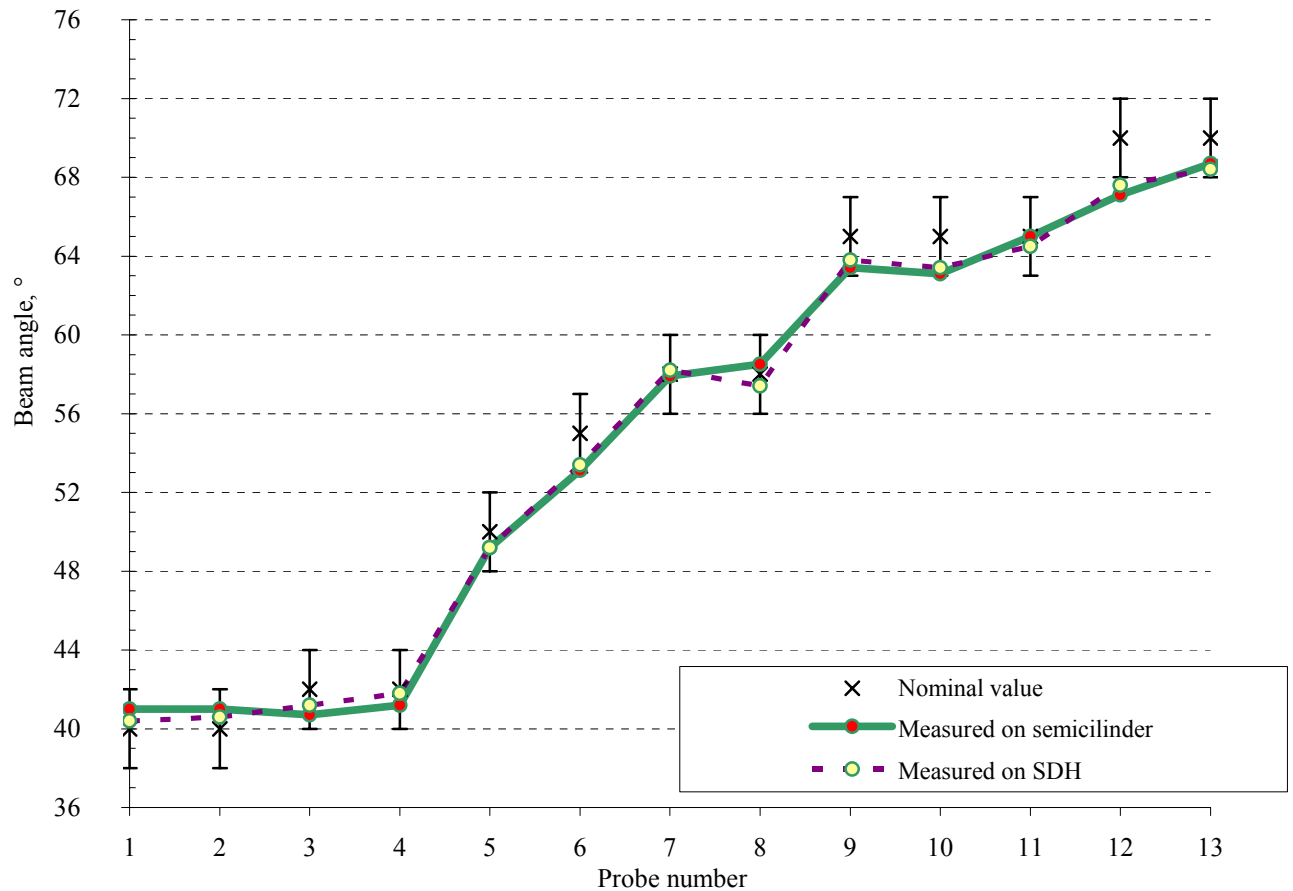
Nominal and mesured beam angles

Fig. 3. The chart of comparison between two methods of beam angle measurement.

Accuracy measurement

The measurement errors were estimated, the R&R (repeatability and reproductivity) analysis of system AUGUR 5.4 as a measuring instrument was completed. First the instrumental errors related to hardware parameters (digitization and sampling of signals, amplifier and scanning device errors) were estimated. Some influence functions of were investigated. Terms and methods of trueness and precision of measuring instruments calculation are described in series on international standards ISO 5725 [6, 7]. Extreme rates of precision are repeatability and reproducibility. The maximal allowed limiting errors in ultrasonic transducers parameters measurements defined in Russian Federation Standard GOST 23702 [8].

AUGUR 5.4 systems allow to measure some parameters directly and to calculate another parameters from ones. The relations between verifiable system parameters and main measured probe parameters shown at Fig. 4. Arrows shows the dependencies. The yellow boxes show some of verifiable system parameters and some influence functions. One can see that certain parameters are located at the end of diagram and as result calculation error is a sum all preceding parameters measurement and calculation errors.
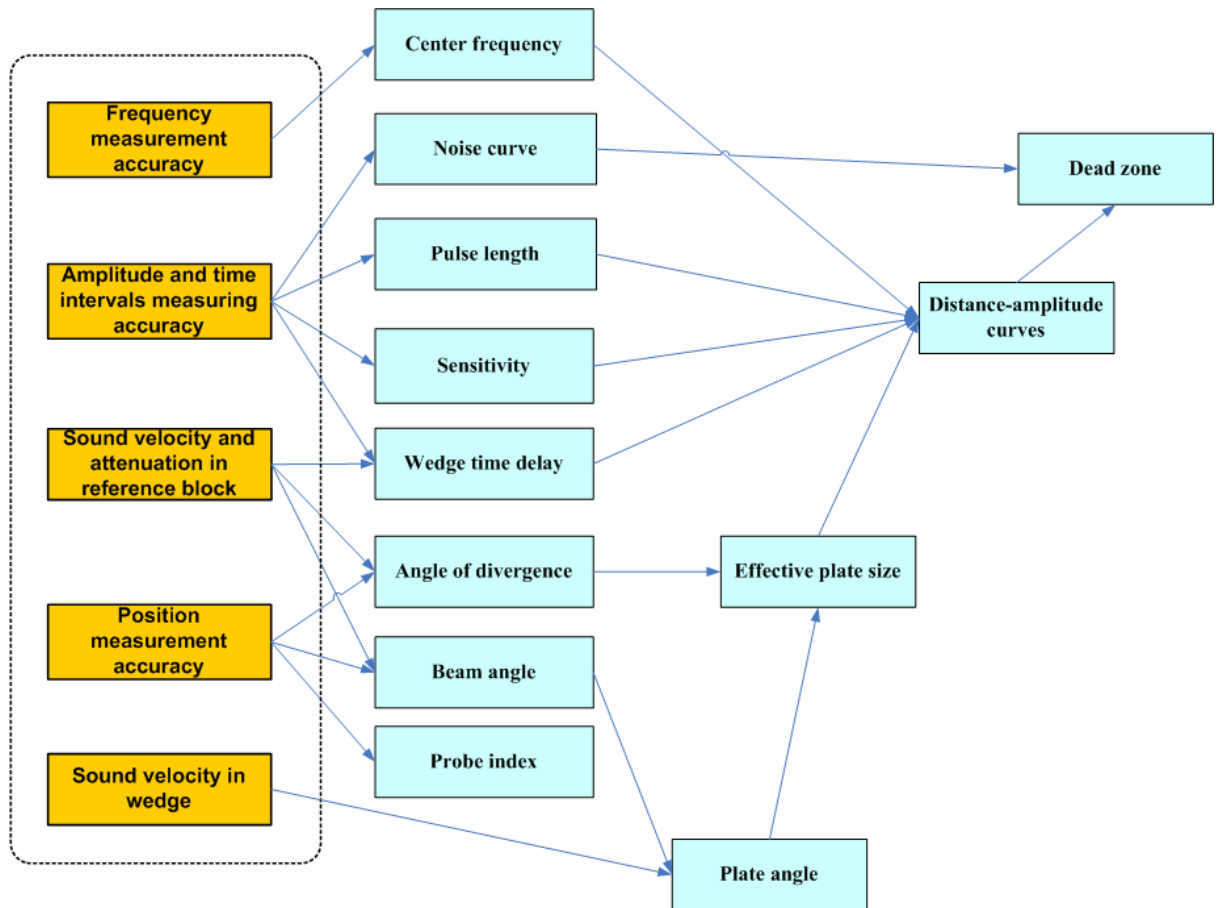
Fig. 4. Scheme of measured and calculated values dependence.

The verifiable AUGUR 5.4 system parameters are

- shock pulse length at 50 Ohms load not exceeding 100 ns with rising edge not exceeding 10 ns
- maximal output impedance with 200 V shock pulse amplitude not exceeding 5 Ohms
- maximal measured signal amplitude at minimal gain must be in range (10±0.1) V
- the limiting error of gain coefficient assertion not exceeding 0.5 dB
- bandwidth at -3 dB cutoff 0.5..15 MHz with inequality not exceeding ±1 dB
- equivalent noise per root bandwidth: $20 \times 10^{-9} \; V / \sqrt{Hz}$
- minimal scanning step size not exceeding 0.02 mm
- the limiting error of scanner position measurement not exceeding 1 mm at 200 mm base (0.5% relative error)

During probe parameters measurement error investigation it was concluded that the foresaid list is complete to fulfill the reproductivity limits.

The instrumental errors was analyzed and the conclusion is:

- limiting sampling error is about 2% for signal with 10 MHz frequency
- limiting frequency measurement error is 10 kHz
- limiting error of sensitivity measurements is about 1.5% (1.2 dB), taken into account the subjective influence of selection signal with maximal amplitude by operator

Some influence functions (sound velocity and attenuation in reference block, temperature and probe position accuracy) of were investigated.

At Fig. 5 shown the theoretical absolute beam angle measurement error dependence on longitudinal sound velocity in reference block error. The curves conforming relative error of sound velocity measurement 0,5 %, 1%, 1,5% and 2%. One can that beam angle measurement error can reach 2° if sound velocity is measured with 1% error. Therefore the reference block datasheet should include the longitudinal and transversal velocities with 0.5% accuracy.

The influence of wedge temperature and reference block attenuation at beam angle value could be calculated easily.

The probe position measurement error (otherwise accuracy of the elementary scanning step – δ_x) have influence on probe index measurement and as well as on directivity pattern measurement. Let see the bias of directivity pattern calculation with use of Fourier transformation in spatial domain holograms spatial spectrum calculation [4]. The relative spectrum sample size error is the same value $\delta k_x = \delta_x$. Error of directivity pattern calculation defined as

$$\Delta\alpha = \alpha - \arcsin\left((1 + \delta k_x)\sin\alpha\right)$$

At Fig. 6 shown can see the theoretical absolute directivity pattern's angle measurement error dependence on relative probe position measurement error 0,5%. One can see that with declared relative position measurement error 0.5% it is possible to reach considerable angle measurement error (0.8° error for nominal angle 70°). But it is necessary to remark that really implemented in AUGUR 5.4 ball-screws guarantees far less error ±(0,05-0,1)%, which was confirm experimentally. So this influence functions could not to be taken into account.

Also the accuracy of calculation the amplitude from SDH at 44 mm depth was evaluated experimentally. Coffecient for recalculation of SDH amplitude from semicylinder bottom of SO-3 reference block is evaluating by Ermolov formula [9]

$$K = \sqrt{\frac{\lambda}{S}\frac{4}{rd}\left(\frac{h}{\cos\alpha}\right)^3} \,,$$

where r – distance to the bottom surface (radius 55 mm), h, d – SDH depth and diameter, α – beam angle, S – plate square (calculated by effective plate size), λ – wavelength. The conclusion from experiments with 12 various types probes is as follows: the mean value of difference between experimental and calculated amplitudes is 1.0 dB, and bias is about +0,2 dB. Thus the calculated parameter has no significant bias.

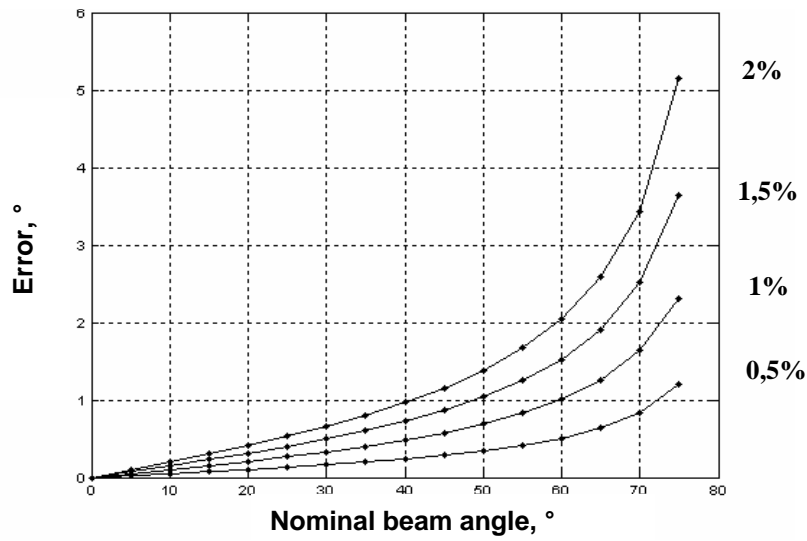**Beam angle measurement error dependence on sound velocity error**

Fig. 5. Theoretical absolute beam angle measurement error dependence on longitudinal sound velocity in reference block error. The curves conforming relative sound velocity measurement error 0,5 %, 1%, 1,5% and 2%.

Angle measurement error dependence on position measurement error
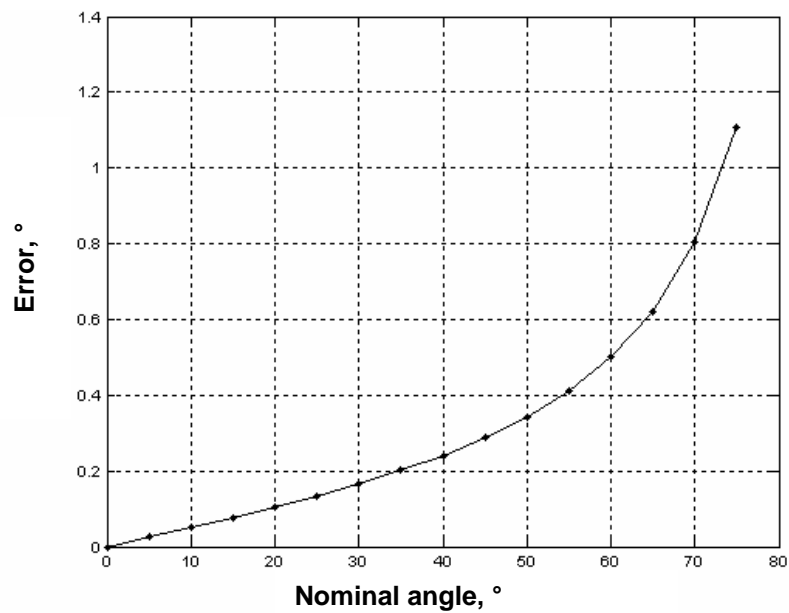

Fig. 6. Theoretical absolute directivity pattern's angle measurement error dependence on relative probe position measurement error 0,5%.

R&R analysis

The R&R analysis with ISO 5725-2 was evaluated. There was used $p = 10$ systems AUGUR 5.4, each of them used to execute $n = 9$ times verification of same transducer with beam angle 70° and operating frequency 2.5 МГц. Systems had a full individual kitting including reference blocks.

The base cells contained the sensitivity, operating frequency, beam angle, beam width, angle of divergence, pulse length, wedge delay time and noise level. The data was checked for consistency and outlets. At Fig. 7 and Fig. 8 the combined data plots shown for sensitivity, wedge time delay, beam angle and probe index. Horizontal axis is the system number (from 1 to 10) at vertical axis is the parameter value. Outlets shown as red crosses, mean values calculated for each system connected by dotted lines.

Table 1 contains results of R&R analysis. The conclusion is

- angle of divergence accuracy is two times greater than beam angle
- equality of repeatability and reproductivity limits for probe sensitivity measurements suggest that electronic parameters of system batch is stable
- the most difference between repeatability and reproductivity limits fixed for wedge delay time and probe index. This means that bias is conditioned by difference in reference blocks properties and scanning device setup accuracy. At Fig. 7, Fig. 8 one can see the variation of mean value from the system number.

One system was used to make probe verification with three different reference blocks and probe parameters compared with ones at the base R&R experiments. So the intermediate measures of the precision [10] was completed. The conclusion is

- beam angle and angle of divergence depends on reference block number
- it confirmed that high reproductivity limit of wedge time delay and probe index is related with reference block properties variation
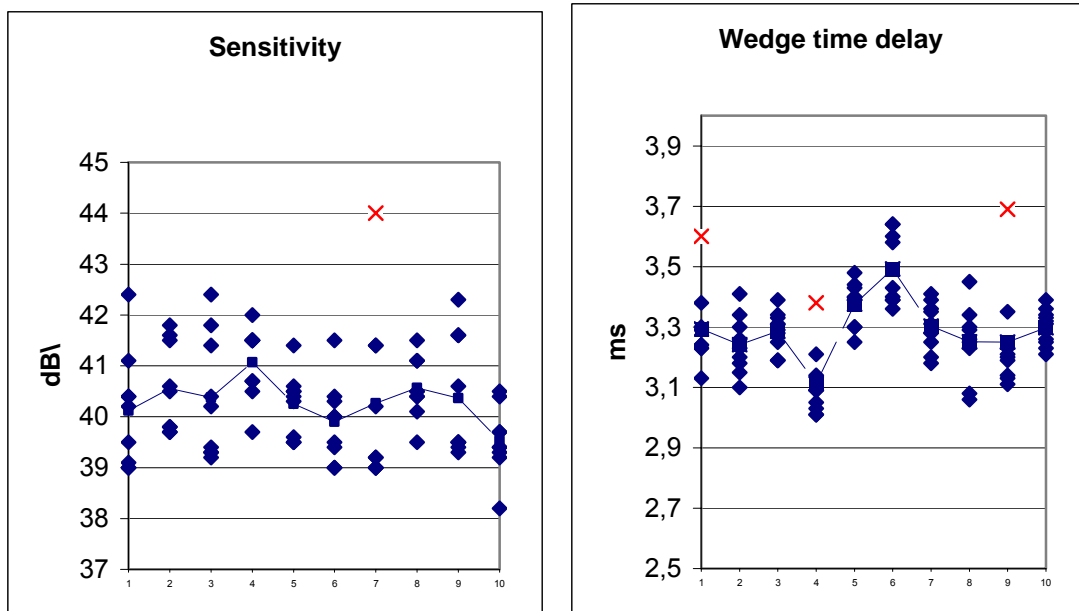

Fig. 7. Sensitivity and wedge delay time measurement results for 9 measurements by 10 systems. Horizontal axis is number of system, vertical axis is measured value. Dotted lines connect mean values for each system. Crosses show outliers.
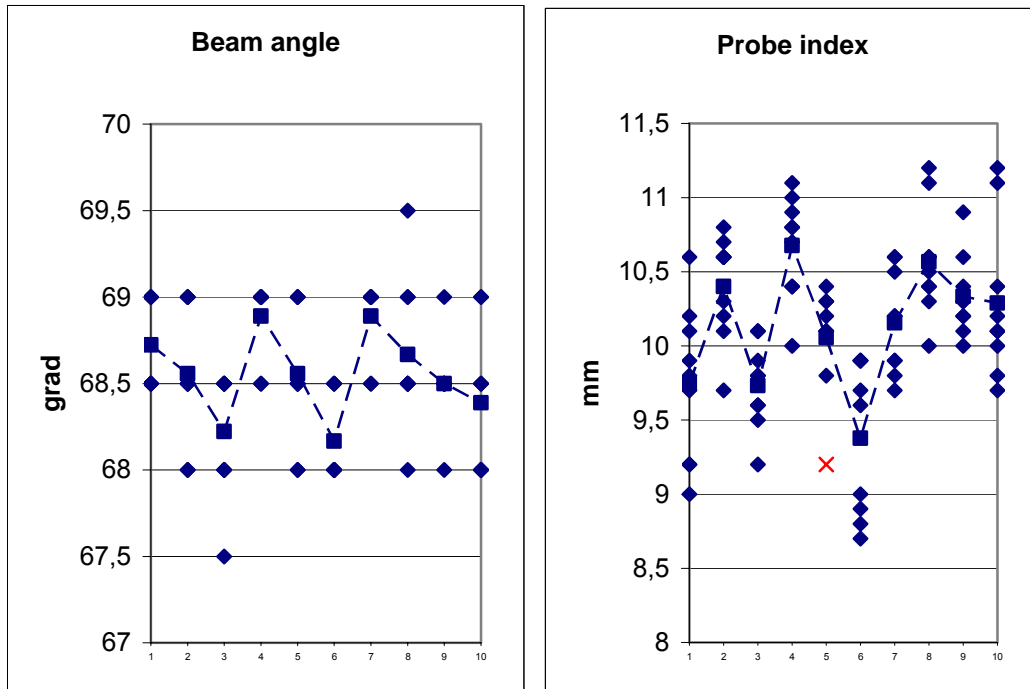
Fig. 8. Beam angle and probe index measurement results for 9 measurements by 10 systems. Horizontal axis is number of system, vertical axis is measured value. Dotted lines connect mean values for each system. Crosses show outliers.

Table 1 Repeatability and reproducibility analysis

Precision values / Probe parameter	Repeatability standard deviation S_r	Reproductivity standard deviation S_R	Repeatability limit r	Reproductivity limit R
Pulse length, μs	0,05	0,06	0,1	0,11
Sensitivity, dB	0,92	0,97	1,8	1,9
Center frequency, MHz	0,005	0,006	0,01	0,01
Index, mm	0,39	0,55	0,8	1,1
Beam angle, °	0,33	0,40	0,66	0,8
Angle of divergence, °	0,51	0,88	1,02	1,76
Wedge time delay, μs	0,09	0,14	0,17	0,27
Noise level, μV	1,03	1,26	2,06	2,52

Table 2 contains the margin limiting errors for some probe parameters. The first column contains the limits of these values according to GOST 23702 for A-class probes. The second column contains this values achieved by AUGUR 5.4 system. All values except beam index are in proper range. The accuracy of probe index measurements is related with manual positioning of probe reference side.

Table 2 Margin of measurement errors

Probe parameter	Margin of measurement error	
	Limit according to GOST 23702	AUGUR 5.4
Pulse length	± 7 %	± 4 % [i]
Sensitivity	± 15 %	± 15 % [ii]
Center frequency	± 5 %	± 0,5% [iii]
Bandwidth	± 4 %	± 1% [iv]
Index	± 0,5 mm	± 1,0 mm

Beam angle
 	
    up to 60°
 	
    over 60°
	
	±0,75°
	
	±1,0°
		
		±0,7°
		
		±1,0°

Summary and discussion

AUGUR 5.4 system allows completing probe verification task without additional metrological equipment (oscilloscope, pulse generator, set of standard blocks, direct current power supply, and plotter etc).

The automation allows reducing the operator's qualification requirements, reducing human factor, providing automatic datasheets generation and storage, checking acceptance criterions, making monitoring and reports with a batch of probes.

The system application recommendations are to specify acceptance criterions for typical probes and to make probe verification at manufacturer site, user site and during the probes` life. System also useful for investigations of non-typical probes and for ultrasonic inspection of compact specimens.

Shown that accuracy of beam angle and wedge time delay measurement requires reference block datasheet to contain sound velocities with ±0,5% accuracy (what is sometimes not fulfilled). The bias was detected while R&R experiments with SO-3R reference blocks.

Shown that verifiable system parameters set is enough to reach reproductivity limit near repeatability limit, the necessary of series manufacturing.

Margin limiting errors for probe parameters is in range stated in GOST 23702 except the probe index. This accuracy could be increased by more careful positioning of probe reference side and multiple determinations of the index value.

More outlets were fixed for wedge time delay measurement. This value measured with manual seeking of echo signal from bottom surface with maximal amplitude. Measurement technique could be improved, for example with comparison of value, measured manually and with automated scanning.

The rounding of values in datasheet grounded: probe index value rounding is 0.5 mm, sensitivity 1.0 dB, wedge time delay 0.1 ms, beam angle and angle of divergence 0.5°.

It is possible to improve accuracy with multiple verifications of single probe. The software modification would be simple enough.

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[i] For 2.5 ms pulse length
[ii] Not taking into account the acoustic coupling variation and sound attenuations is reference block
[iii] For 5 MHz frequency
[iv] For 5 MHz frequency

References

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