# Metrological Self-check of a Transit-time Ultrasonic Flowmeter

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*Abstract. The paper deals with the methods of organizing the metrological self-check in a transit-time ultrasonic flowmeter in which probing of a medium is performed with radiopulses of a specific nature. A method is proposed that allows the uncertainty caused by either the degradation of the flowmeter parameters or the presence of variable density mixtures in the flow, including air bubbles, to be detected and estimated. The results of applying the simulation and prototypes have shown that the uncertainty can be automatically corrected within some limits with the help of the signal processing unit. It is shown too that the time for taking preventive measures and performing maintenance works can be forecasted.*

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## 1. Introduction

Metrological maintenance of sensor devices by means of traditional calibrations with intervals of 1-2 years is economically inefficient and does not exclude receiving unreliable information within this calibration interval.

An alternative is the implementation of the automatic metrological self-check of sensor devices in the process of operation. The checkup of such a type has to increase noticeably the probability of getting reliable measurement results. This means that a sensor device functions properly and conditions under which it operates do not generate any uncertainty that exceeds a permissible value. At the same time, in some cases the metrological self-check can provide a correction of the arising uncertainty, and thereby significantly increase the calibration interval, combining the calibration with a scheduled repair of the equipment with embedded sensor devices.

The metrological self-check is realized in an intelligent sensor device on the basis of a temporary, spatial (structural) or information (functional) redundancy. The redundancy can be detected in a sensor device or introduced artificially.

The metrological diagnostic self-check [1, 2] is an effective approach based on evaluating a deviation of a parameter characterizing a critical uncertainty component from an accepted reference value of this parameter. By the critical uncertainty component they imply a dominating uncertainty component or that one tending to a rapid growth.

The paper deals with the method of measurements of the volumetric water flow rate, as well as with a method connected with it, which allows the metrological diagnostic self-check to be realized. Both methods are intended for using in a transit-time ultrasonic flowmeter (TTF) installed in an industrial power setup.

## 2. A TTF with the simplest probing signal

The principle of operation of such a TTF is based on an effect of the vector addition of the velocity of ultrasound signals and that of water flow where these signals are propagated. This principle provides for measurement of time intervals $t_{a1}$ and $t_{a2}$, within which the ultrasound probing signals pass a known distance downstream and upstream. Then, the results obtained in measurements are processed. The TTF contains a source of electric signals, circuits for transmitting of them, electro-acoustic channel and signal processing unit. The electro-acoustic channel includes a tube of a known section, through which a water flow passes, and two piezoelectric transducers. They are located at a distance called an acoustic base $L$ (see Fig. 1). In some versions of the TTF, in the electro-acoustic channel there are applied reflectors increasing the acoustic base of the TTF.

At present, the TTFs with a high-quality piezoelectric transducers (resonance frequency of 1.0 – 1.5 MHz) are widely applied. These sensor devices are made on the basis of circular piezoelectric discs damped out with a semiconducting compound and guarded with quarter-wave titanic protectors.

In such TTFs the electrical signal source generates videopulses of 0.3 – 0.5 µs duration. They excite 2 - 3 periods of acoustic oscillations in the first transducer with the frequency close to the resonance one. The probing signal in the form of a beam passes the acoustic base in water and enters the second transducer. Accordingly, in the second transducer the acoustical oscillations are transformed into electrical signals. Further, the electrical signal source is connected to the second transducer. Probing in turn with the first and second transducers allows the measurement cycle duration to be determined.

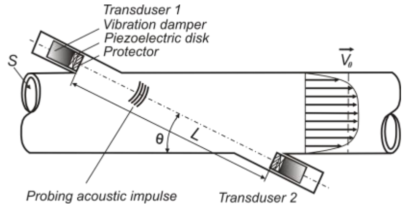



Fig. 1. Structure of an electro-acoustic channel of the TTF.

By neglecting an inequality of local velocities over the sections and along the length $L$, the volumetric flow rate of water can be estimated as:

$$F = S \cdot V_0 = \frac{S \cdot L}{2\cos\theta} \cdot \left\{ \frac{1}{t_{a1}} - \frac{1}{t_{a2}} \right\} = K \cdot \left\{ \frac{t_{a1} - t_{a2}}{t_{a1} t_{a2}} \right\}, \quad (1)$$

where $V_0$ is the velocity of water;
$K$ is the coefficient depending on the tube geometry;
$S$ is the area of the tube cross section;
$\theta$ is the angle between the vectors of flow and ultrasound velocity.

For the TTFs applied in industrial power setups, the permissible uncertainty of measurements does not exceed 1%, the ratio of the flow velocity to that of the ultrasound velocity being no more than $5 \cdot 10^{-3}$. The TTF with a diameter of the tube equal to 50 mm, $\theta = 45^o$ and $L \approx 70$ mm can be used as an example.

For $V_0 \geq 0.9$ m/s and the sound velocity in stationary water, $c =$ 1500 m/s (at 20 $^o$C), $t_{a1} \geq L/(c - V_0 \cos\theta) = 46.686275$ μs;
$t_{a2} \leq L/(c + V_0 \cos\theta) = 46.647075$ μs; $t_{a1} - t_{a2} \geq 39200$ ps.

It can be noticed from these calculations that the time intervals being measured are very small and the uncertainty of measurements have not to exceed (150 -200) ps. At the same time, the requirements to the metrological reliability of sensor designs are very high, since the task is posed to increase the calibration interval for such TTFs up to 10 and more years.

In the process of many-years operation under the influence of vibration, water flow with a solid particle mixture, as well as of the other factors, the geometry parameters of the flowmeter tube change. These changes are relatively slow. When the quality of manufacturing the tubes is sufficiently high, their effect on the measurement uncertainty within the 10-years calibration interval can be neglected.

The metrological serviceability of electronic units outside the TTF tube, i.e., of the signal source and signal processing unit as well as of the electrical circuits connected to them, can be easily checked up automatically in the process of operation.

The operable condition of the TTFs, with respect to metrology, is also subjected to the influence of unstable characteristics of the piezotransducers and water flow. The piezotransducer parameters can change when the temperature increases as well as due to their aging [3]. Variation of the temperature and acoustical properties of the water flow is connected with a change of the mode and operating conditions of the power setup. Since the air content in water can reach 5% or even more, a decrease of pressure which accompanies a decrease of the water flow rate generates the occurrence of air bubbles and other acoustical inhomogeneities, e.g., curls.

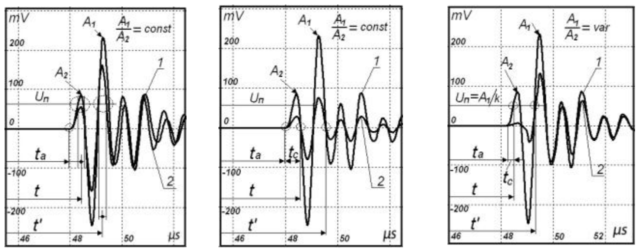
The instability of the characteristics indicated leads to a distortion of the shape of a signal received. This manifests itself in the uncertainty of measuring the time intervals $t_{a1}$ and $t_{a2}$. The uncertainty of measuring the intervals significantly depends on the method chosen for recording the moment when the probing signal arrives and on its shape too.

To the conventional methods of recording the moment the received signal arrives, they refer the so called "threshold" ones:

- "centroid of area" method [4] which provides for that the average time value between the moments when the signal received passes a threshold upward and downward, is taken as the moment of recording;
- "zero-crossing" method [5] which provides for that the moment when the signal crosses the "zero" line from downward, is taken as the moment of recording;
- "sliding threshold" method [6] which provides for that the maximum level of the signal received is measured, then a threshold that is a fractional part of the maximum level, is set (i.e., the threshold corresponds to some phase of the signal received).

All these methods ensure a fixation accurate enough for a representative point of the signal received when its amplitude varies within the limits wide enough.

Application of these methods implies recording the moment of the signal arrival with a delay $t_c \leq T/2$. This delay (in addition to the delay caused by other reasons typical for the TTF design chosen) distorts the calibration characteristic. However, the influence of $t_c$ on the uncertainty can be reduced to a minimum at the approximation of the calibration characteristic with the polynomial $a+bF=cF^2$ and determination of the coefficients $a$, $b$, $c$ at the stage of calibration. Application of a higher order polynomial also is possible. The diagrams given in Fig. 2 show how the shape of the signal received is distorted when the temperature rises and acoustical properties of the water flow change, as well as how the uncertainties originate in case of applying methods considered. The diagrams have been obtained with the help of PSpice model of the TTF piezotransducer [7, 8] and Micro-Cap9 software.



a) b) c)

Fig. 2. Influence of various processes on the shape of the signal received (PSpice model)
a) Heating: 1 – a piezodisc at 20°C; 2 - a piezodisc at 180°C; "centroid of area"method
b) Decrease in acoustical water transparency: 1 – settled water; 2 – tap water; "zero- crossing method"
c) Appearance of air bubbles: 1 - settled water; 2 - presence of a "cloud" of bubbles; method of a "sliding threshold"

The rise in temperature of the transducers and change of both the resonance frequency of piezodiscs and acoustical resistance of the protectors, caused by this rise, as it follows from Fig. 2a, changes the period of free oscillations of the piezodisc. This leads to a consecutive displacement of the centroid areas of half-waves. The shape of this signal can be considered as a sinusoidal one only conventionally. The difference between the first half-waves duration values and the nominal value, which corresponds to *T/2*, increases with temperature depending on a quality factor *Q* of the piezotransducer. For example, when the temperature increases by 160 °C and $Q \cong 30$, this difference reaches 20%.

The decrease of acoustical water transparency due to undissolved air in it (Fig.2b) results in a noticeable drop of the signal amplitude, but does not practically affect the points of crossing the "zero".

The appearance of acoustical inhomogeneities in the form of small bubbles (1 – 10 μm) leads to the absorption of the ultrasonic oscillation energy caused by the resonance properties of the bubbles.

An equivalent area of the bubble zone, where the resonance absorption takes place, exceeds by some thousand times the total area of their section, even in the case of relatively great differences in bubble dimensions. The appearance of the air bubbles of small dimensions in the water flow results in a qualitative change of the shape of the first half-waves of the signal received (Fig. 2c).

The influence of the bubbles and other acoustical inhomogeneities of significantly greater dimensions is reduced to the scattering of an ultrasonic beam. A shielded part of the beam cross-section area depends on their volume concentration.

To confirm the correctness of the model applied, the bubble "cloud" influence on the propagation of ultrasonic oscillations was checked up with a prototype in which the electro-acoustic channel (with a length of 198 mm) was simulated with a cuvette filled in with water. On the opposite edges of the cuvette, two piezotransducers with an oscillation frequency of 1,05 MHz were installed. A controllable d.c. voltage source (20 -50 mA, 12 V) and a set of spiral electrodes of 0.08 mm in diameter were used to generate hydrogen bubbles with the help of the electrolysis method. The optical transparency of the water remaining unchanged, the appearance of the "cloud" of fine-dispersed bubbles, which contained (0.2 - 0.3)% of air, resulted in a sharp attenuation of the ultrasound and generation of a noise background in the process of receiving the signal. The comparison of Fig. 2c with the oscillogram shown in Fig. 3 demonstrates the efficiency of using the PSpice model.

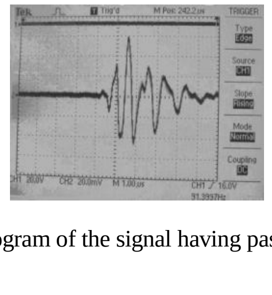


Fig. 3. Oscillogram of the signal having passed through the "cloud" of bubbles

It should be emphasized that the methods of recording the moments the signal arrives, are effective only provided the signal-to-noise ratio is high enough, i.e., when the wavefront steepness is high. In practice the level of acoustic noise in an operating power setup is significant. The signal amplitude can be noticeably decreased. The probability of recording the moment of the signal arrival by the second or even the third period, i.e., with a crude uncertainty of the flow rate estimation, is noticeable.

In [9] it is proposed to get a sharp leading wavefront by passing the signal received through a specialized filter-corrector providing a high robustness with respect to signal parameter variations. However, such an approach keeps a delay $t_c$ of the moment of recording the signal arrival and an uncertainty connected with it, which is caused, in general, by the ambiguity of the received signal shape.

Thus, the method of ultrasonic probing, which is above considered, does not provide reliable measurement results under real operation conditions of power setups.

At the same time, the maximum probability to get unreliable results of flow rate measurements is connected with variation of acoustical water properties, caused, first of all, by the appearance of the air bubbles in a flow. The corresponding uncertainty component can be recognized as the critical one.

What is the potential for increasing the reliability of measurements using simultaneously the method of ultrasonic probing which is considered above and metrological self-check?

The ability to arrange the metrological self-check in measuring the flow rate is defined taking into account the critical uncertainty component, redundancy, which can be revealed or artificially introduced into the TTF, as well as economic criterion.

With reference to the TTF considered, in arranging the self-check it would be possible to take into account the fact that the water flow velocity cannot sharply change. On this basis it is possible to fix the abrupt changes of the signal propagation time, which take place due to a shift of the signal registration moment by a half-period or its multiple intervals. On the basis of such a check it is possible to separate repeating intervals with a minimal time of propagation as the most reliable ones.

The piezotransducers degradation generating the variation of the calibration characteristic coefficients can be, to a certain extent, checked up automatically by comparing the measurement results obtained over a long period of time (in sufficiently close operation modes of the power setup), and revealing their trend.

However, these decisions do not provide the required accuracy of the self-check. The redundancy found in the TTF is not enough for a positive answer to the question put forward.

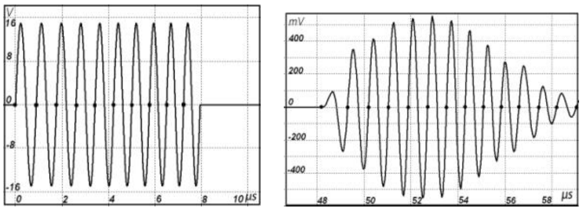
In principle, it would be possible to proceed by introducing a structural redundancy, i.e., using additional electro-acoustical channels.

Since the bubble "clouds" and other acoustical inhomogeneities are distributed, as a rule, irregularly over the cross-section of the tube, it is possible to use in the TTF a number of beams and consequently a number of electro-acoustic channels for increasing the reliability of the measurement results. The beams should be located in a way that can provide decreasing the influence of the flow mode (a turbulent, laminar, or transient one) [10]. In this case the check is implemented by comparing the results obtained in different channels. As an auxiliary means for implementing the self-check, additional transducers can be used. They provide measurements of the time within which the signal propagates in the cross-section of the tube [11]. At the same time, it is possible to check changing in time of the delay in the piezo-transducer protector.

Such decisions are useful, but within a wide range of changes of the electro-acoustic channels characteristics, they do not provide the accuracy required.

## 3. The TTF with information redundancy of the probing signal

The similarity between the methods of the information transmission-reception in the electro-acoustic channel and communication systems can become a basis for performing the search planned. The response of the piezodisc to its excitation with a videopulse resembles an amplitude-modulated signal that provides a sufficiently band limited communication, but at the same time, the least noise-immune one. When the piezodiscs distinguished by a comparatively high *Q*-factor are used, application of a frequency-modulated signal according to that suggested in [12] causes a long transient process ( see Fig. 4).




a) b)

Fig. 4. Distortion of the frequency-modulated signal of the TTF (PSpice model)
a) the signal transmitted by an "ideal" piezotransduser; b) the signal received

An alternative is the transfer to the phase-modulated (PM), in particular phase-manipulated signal.

Essentially, the transfer to the phase manipulation corresponds to the suggestion made in [13] to use a "mark" of time in the signal. Such marks are determined by introducing one or a number of preliminary known disturbances into the probing signal on the background of stable oscillations. The marks can be identified in analyzing the transient process.

At small modulation indices, the frequency band occupied by the PM signal is sufficiently small and close to the band of an amplitude-modulated signal, but when the index rises, it rapidly increases. The choice of an index depends on an appropriate signal-to-noise ratio under expected operating conditions of the TTF.

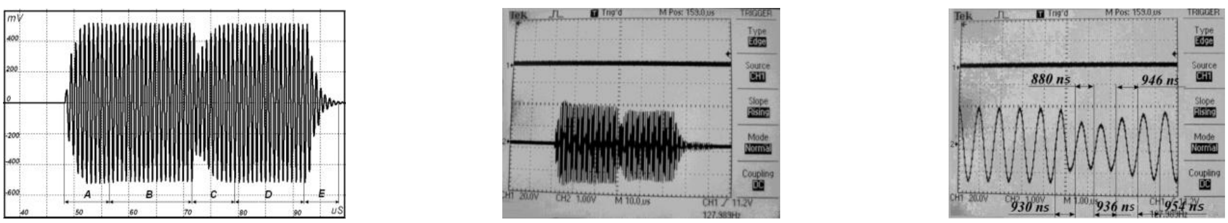
At the same time, since there is no possibility to implement an ideal damping and exclude the resonance properties of the protector, in the latter the reverberation takes place. This results in a loss of energy. The greater the angle of manipulation is, the less the coefficient of the transducer transmission is. On the other hand, a decrease of this angle leads to a poor recognition of the mark.

The choice of the manipulation angle essentially depends on a method of the received signal demodulation. Application of a quadrature demodulating sequence restricts the phase angle of manipulation to an upper limit of $90^{\circ}$ and the range of optimal angles of manipulation to $(30 - 60)^{\circ}$.

In modeling and prototyping the TTF with informational redundancy of the probing signals, a sequence of cyclically transmitted radiopulses (with a period of 0.01 s) was applied. Each radiopulse, containing 56 periods of the resonance frequency ($T$=960 ns), excited the first piezotransducer. One of the periods (the 30-th one) was shortened by an angle of $\varphi_m = 60°$ (160 ns). For the prototype a signal processing unit based on CPLD matrices of the "CoolRunner XPLA3" series ("Xilinx") was developed.

The excitation signal was shaped by "conglutinating" fragments of sinusoids in the PSpice model and by rectangular unipolar pulses in the prototype. In Fig. 5 the time diagrams of the signals received are shown for the case when there are no bubbles in the elecro-acoustic channel. They were obtained with the help of the PSpice model and prototype.

In zones B and D, steady state behavior with the period equal to the resonance one can be seen. The zone C corresponds to the transient process caused by the phase manipulation. It is similar in time and nature to that observed in zones A and E. The comparison of Fig. 5a and 5b demonstrates that the PSpice model adequately reflects the processes taking place in the TTF when the PM radiopulse is used. Fig. 5c illustrates the nature of the transient process taking place in zone C. In this zone, the deviations of the period $|T_i - T|$ vary gradually (30, 80, 26, 14, 6, 2, 2, 0, 0, 0 ns), the total shift by 160 ns achieving within the seven periods at a given *Q*-factor. If the *Q*-factor changes, the gradual variation of the period duration can be observed in the course of 6 – 10 periods.



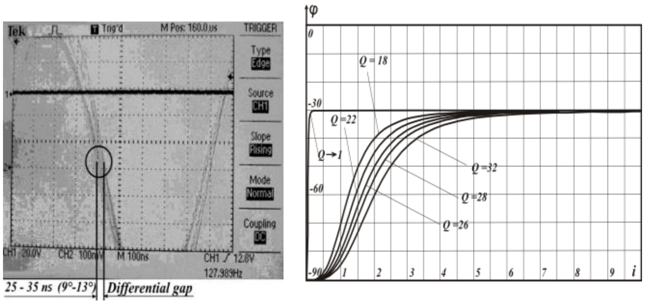

a) b) c)

Fig. 5. The signals received in the case of applying the PM radiopulse (there are no bubbles in the elecro-acoustic channel)
a) according to the PSpice model; b) and c) according to the experiment with the prototype.

The bubbles and other acoustical inhomogeneities can significantly decrease the amplitude of the PM signal and generate its "jitter", which is shown in Fig. 6a. However, the phase instability caused by the "jitter" is significantly less than $\varphi_m$ given. Unlike the signal obtained in using the videopulses, the PM signal generates additional (redundant) information about the place occupied by the "mark", which allows the accuracy of measuring the time of the signal propagation in the presence of acoustical inhomogeneities to be significantly increased.

The distribution of deviations $|Ti - T|$ over the length of the radiopulse for the given angle values $\varphi_m$ and $Q$-factor of the transducer piezodisc can be determined and, if necessary, reproduced in the receiving part of the TTF.

The $Q$-factor of the piezodisc in the process of operation varies as a result of heating and aging of the material. This affects the distribution of deviations $|Ti - T|$. The stability of this distribution in the process of the TTF operation is illustrated in Fig. 6b, where for each $i$-th period of the zone C, the dependence of the current phase $\varphi$ on the $Q$-factor of the transducer is given (the original value of the current phase $\varphi_0$=-90°, $\varphi_m$=60°). From Fig. 6b it follows that the variation of the $Q$-factor within the limits of 25±7, which is possible in the process of the TTF operation, does not practically change the nature of the time period distribution during the transient process at the phase manipulation.




a) b)

Fig. 6. Variation of the phase in the zone C
a) "jitter" of the signal in the prototype; b) variation of the phase for various periods of the PM radiopulse depending on the $Q$-factor of the piezotransducer (PSpice model).

Thus, the following procedure of measurements can be used.

The signal transmitted with the built in "mark" is reproduced by a digitized "record". The signal received is digitized and recorded, the moments of finishing periods being determined, e.g., according to the "zero-crossing" method, and then it is compared with the reference signal.

The image of the signal received under "ideal" conditions plays the role of the reference signal. Using the control system included in the signal processing unit, the reference signal travels along the time axis with a delay controlled. In a special phase detector it is compared with the received signal which has been recorded before. The structure and operation algorithm of the phase detector provide an increased sensitivity and accuracy. The best coincidence of the signals is fixed when the reference signal shift is 90° with respect to the signal received, i.e., the reference signal performs the function of a quadrature demodulating signal. The speed of the controlled delay variation has to decrease rapidly as the point of the best coincidence is approaching. The "mark" being detected in the radiopulse received, it is possible to determine its location more exactly using information about the time when the resonance frequency oscillations preceding this "mark" and following it later on, arrive. The known distribution of deviations in the radiopulse received should be taken into account in this procedure.

A further improvement of the time measurement accuracy can be realized by analyzing the parameters of subsequent radiopulses.

The delay time experimentally determined after subtraction of the signal delay time in the transducer protectors and signal processing unit, corresponds to the time of the ultrasonic signal propagation in water flow.

To provide the metrological self-check, it is possible to use the dynamics of the controlled delay time from one radiopulse to another.

If in the process of operation the delay time fluctuates within the limits of the required measurement accuracy or keeps to be constant, the TF should be considered as the metrologically operable one. At the same time, in case when the delay time is constant within a significantly long period, e.g., more than 10 s, it should be automatically changed within the limits of a tolerance to check the serviceability of the control system. If the change introduced is automatically compensated, then the metrological operability of the TTF is confirmed. In the opposite case the device is not serviceable.

Aside from checking such failures, the metrological self-check has to fix automatically malfunctions and dangerous trends, e.g., a gradual expansion of control boundaries, increase of a number of cases when such an expansion of the boundaries takes place, and some other changes in the normal dynamics of operation. Signals informing about the dangerous trends should be considered as "alarm" information, showing a decrease of the measurement results reliability, growth of the uncertainty or possible failure.

At the same time, it appears to be possible to forecast a time interval the flowmeter uncertainty caused by the degradation of its parameters, will not go outside the permissible limits. Information about the current flow rate at a fixed malfunction in the operation of the control system has to be blocked before repairing the latter.

The application of PM radiopulses, aside of the self-check function, provides the possibility to increase significantly the accuracy of measuring the time of the ultrasonic signal propagation on the basis the information redundancy, including the case when the acoustical inhomogeneities appear. Correspondingly, the flow rate measurement accuracy and reliability of the obtained measurement results are increased.

The efficiency of the method considered above was tested using the TTF prototype with a PM signal. Between the transducers there was generated a "cloud" of bubbles. It caused some "jitter" leading to an uncertainty in determining the moments of oscillation arrival within the limits of (25 – 35) ns in the signal zone C.

The information redundancy of the probing signal allowed the instability of the TTF readings, caused by the noise of the signals received, to be significantly decreased.

The signal processing unit changes a preliminary found delay time on the basis of a number (more than 20) signal characteristics rather than one (as it takes place in case of the traditional TTFs).

In developing the prototype, attention was drawn to the need to reduce (up to less than 1 s) the time of setting reliable readings of the TTF after its switching on. The fact is that at an unknown water flow rate, the uncertainty of the moment when the signal arrives lies within the range of tens μs. In controlling the delay time with the discreteness of 10 ns, when the control speed is constant, the determination of the water flow rate could take 10 s. To reduce this time an algorithm implemented with the help of the Moore automaton was used as the algorithm of the control system operation. It is supposed that at the one-sided displacement of the reference signal relative to the signal received, this algorithm provides the possibility to change the control step from a preceding radiopulse to a subsequent one with doubling the latter, i.e., to use the values 10; 20; 40; 80; 160; 320; 640; 1280 and 2560 ns. As a result the time spent for determining the moment of the signal arrival will not exceed 0.22 s.

When the frequency of probing cycles was equal to 100 Hz and the time of averaging was 1 s, the uncertainty of determining the time of signal propagation was close to 70 ps, which was enough for the TTF of the power setup.

A further increase of the measurement accuracy can be achieved by increasing the duration of the PM radiopulse, optimizing the angle of PM and/or improving the accuracy of recording the reference and received signals, which is determined by the clock frequency (in the prototype it was the equal to 100 MHz).

The decisions suggested can be combined with some known methods of increasing the reliability of flow rate measurement results [10, 11].

## 4. Conclusion

The metrological self-check allows the reliability of measurements obtained with the help of the transit time ultrasonic flowmeter applying the simplest probing signals to be increased.

However, significantly better results with respect to both the reliability and accuracy of measurements can be achieved by using a probing signals with an increased information redundancy. A radiopulses with the phase manipulation can be used as the signals of such a type.

In the flowmeter with a phase-manipulated radiopulse, the increased accuracy of measurements under the conditions of a significant acoustical inhomogeneity of the flow, can be achieved using the method of comparison of the signal received with a reference one, the delay of which is controlled up to the maximum coincidence of the signals.

At the same time, the metrological self-check can be implemented by an analysis of the dynamics of the controlled delay. Such a check detects changes of the flowmeter parameters in the process of operation, reveals and allows the uncertainty caused by some degradation of piezotransducers to be corrected, responds to the appearance of acoustical inhomogeneities in water, e.g., air bubbles, and provides grounds to forecast the time for taking preventive measures and performing maintenance works.

Applying such flowmeters will make it possible to:

- increase noticeably the accuracy and reliability of measurement results;

- sharply reduce man-hours for the flowmeter maintaining due to a significant increase of the calibration interval and transfer to the condition-based maintenance.

## REFERENCES

1. Taymanov, R. and Sapozhnikova, K., “Problems of Terminology in the Field of Intelligent Sensors and Systems,” Key Engineering Materials, Vol. 437, pp 434-438, Trans Tech Publications, Switzerland, 2010.
2. Taymanov, R. and Sapozhnikova, K., “Metrological Self-Check and Evolution of Metrology,” Measurement, Vol. 43, No. 7, pp. 869-877, 2010.
3. VDI/VDE Guideline 2650 Requirements for Self-monitoring and Diagnostics in Field Instrumentation, 2005.
4. US4079315, G01R29/02; G01V1/30, Mohr, W., “Method and Apparatus for Measuring Time Interval between Two Pulse Signals,” filed: 23.02.1976, publ. date: 14.03.1978.
5. US3690154, G01B17/02, Wells, F.H., Martin, R., “Apparatus for Measuring Thickness,” filed: 17.07.1970, publ.: 12.09.1972.
6. RU 2210062, G01F 1/66, Malkhazov, Ju.S., Kozobrodov, V.A. and Gurevich, V.M., “Ultrasonic Flow Meter,” filed: 19.06.02, publ.: 10.08.03.
7. Leach, W. M., “Controlled-source Analogous Circuits and SPICE Models for Piezoelectric Transducers,” IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 41, pp. 60–66, Jan. 1994.
8. Puttmer, A., Hauptmann, P., Lucklum, R., Krause, O. and Henning, B., “Spice Model for Lossy Piezoceramic Transducers,” IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 44, pp. 60–66, Jan. 1997.
9. Barkhatov, V.A., “Normalization of Ultrasonic Pulses in the Systems Intended for Measuring the Values of Delay and Distance,” Defectoscopy, No.6, pp. 76-82, 2009.
10. http://www.krohne.com/ALTOSONIC_V_Ultrasonic_Flowmeters_en.162.0.html
11. RU 2106603, G01F 1/66, Malkhazov, Ju.S., Kozobrodov, V.A., Gurevich V.M., “Ultrasound Flowmeter,” filed: 12.02.1997, publ.: 10.03.1998.
12. Latino, C.D., Andersen, N.L. and Voss, F. “Detection of Time of Arrival of Ultrasonic Pulses,” Mathematics for Industry in Denmark, Journal of Physics: Conference Series 52, pp. 14–26, 2006.
13. US6062091A, G01F1/66, G01N29/024, G01P5/18, Baumoel, J., “Method and Apparatus for Determining Ultrasonic Pulse Arrival in Fluid Using Phase Correlation,” filed: 22.04.1997, publ.: 16.05.2000.