Development of the experimental equipment for measuring the velocity of ultrasonic waves with high accuracy

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Abstract. The article considers the development of installations for measuring the velocity of ultrasonic waves, implementing auto-circulation, echo-pulse and resonance methods. The aim of the work is to improve the accuracy of velocity measurements, automation of the measurement process, the possibility of cross-matching the results, the use of techniques related to the precise velocity measurement and the evaluation of acoustic frequency-response characteristic for determining the physical properties of objects and other tasks of non-destructive testing.

1. Introduction
Accurate measurement of ultrasonic vibrations velocity in various objects and media is an urgent technical problem. Despite the high development level of modern flaw detection technology, at the moment there are practically no serial devices that implement this task. Perhaps this is due to the fact that with increasing requirements for accuracy, the role of interfering factors and errors significantly increases, the influence of which in traditional ultrasonic testing can be not taken into account. Among them there are the influence of the contact fluid layer thickness and the roughness of measured surface, the difficulty in determining the exact time of the ultrasonic pulse arrival. In addition, it is necessary to take into account changes in the frequency spectrum of pulses at different passed distances, the influence of geometry of an object.

These factors are partially minimized by the use of contactless transducers, mathematical signal processing (finding the maximum of the correlation function), or by the use of techniques in which the part of mentioned errors is compensated in various ways [1]. For example, in the structurescope SEMA, developed at the Chair of “Devices and techniques for measurements, testing and diagnostics” (DTMTD) of the Kalashnikov Izhevsk State Technical University, two mutually perpendicular coils that excite transversal waves of corresponding polarization are used, and the measured parameter is the difference in the run times of ultrasonic pulses [2]. However, this method is also not universal, since it is focused on the registration of transverse and Rayleigh waves.

2. Installations for measuring the velocity of ultrasonic waves
For more in-depth study of the factors influencing the accuracy of measurement of the ultrasonic waves velocity, a set of measuring equipment at the Chair of DTMTD is produced consisting of three units:
- the acoustic wave velocity meter (AWVM) implementing auto-circulation method [3];
2.1. The acoustic wave velocity meter (AWVM)

The generator of probing pulses of the device works in the autotimer mode, i.e., the signal at its output appears only after the triggering pulse from the receiver comes to its input. The signal of the generator is fed to the transmitting transducer and, passing through the tested object, gets to the receiver. The received pulse after amplification starts the generator again. The process repeats. The frequency measurement unit records the repetition rate of signals \( f \). The sound velocity is determined by the expression:

\[
v = \frac{f d}{1 - f(t_a - t_e)},
\]

where \( d \) is the distance traveled by the ultrasonic wave in the tested object; \( t_a, t_e \) – acoustic and electric delays caused by the propagation of signal in prisms of transducers and the actuation time of electric circuit components of generator, amplifier, pulse shapers. The velocity measurement accuracy by the use of auto-circulation method is about \( 10^{-2} - 10^{-3} \) [3-5]. The device is implemented on the basis of a microcontroller, the block diagram and appearance are presented in Figure 1.

![Figure 1. Block diagram and appearance of AWVM device: 1 - transmitting transducer, 2 - receiving transducer.](image-url)
The disadvantage of the device is the inability to use waves of other types, except surface waves. Since the bulk waves have significantly less attenuation, when working in the auto-circulation mode, a plenty of reflected pulses are formed disturbing the work of the pulse registration module.

2.2. The ultrasonic wave velocity meter based on the use of the echo-pulse method
The use of classical echo method allows to overcome this drawback of AWVM device despite the more complex implementation of the required accuracy [6-8]. Accordingly, the second modification of the device for measuring the ultrasonic wave velocity uses the echo pulse method.

![Block diagram of the echo-pulse method velocity meter](image)

**Figure 2.** Block diagram of the echo-pulse method velocity meter: 1 – microcontroller; 2 – LCD display; 3 – controls; 4 – high voltage generator; 5 – probing pulse generator; 6 – negative voltage converter; 7 – piezoelectric transducer; 8 – voltage tunable amplifier; 9 – comparison element; 10 – peak detector.

The main advantages of the device are: the presence of an automatic gain control system minimizing the amplitude-time modulation of the device indication, the possibility of software averaging the results or more complex mathematical processing, the flexible adjustment to the frequency parameters of transducer and the measurement conditions. In addition, there are reasons to assume that with increasing the requirements for measurement accuracy, it is necessary to take into account the change in spectral composition of the pulse at different thicknesses; for this purpose the corresponding correction factors can be introduced into the device software. Since the control of the measurement process is determined by the microcontroller firmware, it is possible to quickly change the conditions of the experiment (synchronization of external events, the possibility of using non-standard acoustic transducers).

As an example, the measurement results of the time of ultrasonic waves propagation in two cylindrical samples with a small difference in length are presented in Table 1. The measurement accuracy achieved is about 0.2 %. Calculated difference measured by micrometer – 0.12 mm. Experimental difference measured by echo-pulse method – 0.15 mm.
Table 1. Results of measurement of the time of ultrasonic waves propagation in two cylindrical samples.

| Parameter                           | Sample 1 | Sample 2 |
|-------------------------------------|----------|----------|
| Thickness measured by micrometer, mm| 48.30    | 48.42    |
| Time of the pulse arrival, ms       | 17.04    | 17.09    |

2.3. The installation for measuring the velocity by a resonance method

It is known that to set up or calibrate a device that implements a particular method of measurement, the use of equipment or techniques that provide (at least in particular cases) significantly higher accuracy characteristics is required. Since the resonance method is one of the most accurate, there is a need for its hardware implementation. To solve the task, the components used in the development and ways of their interaction are defined as follows. The generation of the signal is provided by a specialized chip AD9833 receiving a command word from the controller only in the time moment of frequency switching, therefore, there are no special requirements to operating speed of the microcontroller, so any of available microcontroller platforms can be used. To facilitate debugging of the software, information about the frequency values is displayed on the liquid crystal indicator of standard type. An incremental encoder is also used as a standard control.

The installation operation is based on the following algorithm. The initial and final values of the operating frequency, as well as the scanning step, the frequency change rate and other parameters are being set using the encoder. Data are transmitted to the generator chip, from which the signal is fed through the matching cascade to the object of measurement. Then, to register the output signal amplitude, a peak detector is used, the data from which, with a reference to the current frequency, are periodically read through the internal analog-to-digital converter of the microcontroller. The frequency and amplitude data as a character string are transmitted to a personal computer. Thus, the frequency response of studied object is actually measured, the position of resonances on which contain the information on the exact value of the ultrasonic waves velocity. The complete block diagram of the device under development is given in Figure 3. The developed software should provide visualization of the received frequency response, and in addition should provide functionality that allows to:

- compare two or more frequency responses for detailed analysis;
- set parameters of the signal from the personal computer;
- save acquired frequency responses to files of standard formats for their further analysis;
- develop additional functions to optimize a particular study.

**Figure 3.** Block-diagram of generator installment for studies of frequency response of acoustic transducers.
To verify the efficiency of developed installation and the degree of its applicability for studies based on the resonance method, a piezoelectric-crystal plate PZT of size of 20×9×0.75 mm with a resonant frequency of 3 MHz, as well as a standard piezoelectric transducer P-111-2.5-5 were connected to the output of generator. The frequency response diagrams obtained are presented in Figures 4–7. The graphs indicate that operation of the installation is correct: the positions of the resonance frequencies and the nature of changes of resonance curves in case of loading coincide with the theoretical ones. Therefore, this unit can be used for various measurements using the resonance method. Considering the high frequency resolution of 0.1 Hz for AD9833 chip, the obtained results can be expected to have an accuracy higher than 0.1 %. In addition, a number of more complex problems could be solved by this method in the future. For example, in Figure 7 in addition to the main resonances, there are components of higher orders conditioned by radial reflections (an object is cylindrical). At the same time, even minor changes in the wave pattern are confidently recorded. Therefore, this method can be used in operational testing (evaluation) of complex shape products compliance with standard samples, where ordinary methods of sounding may not be applicable.

3. Conclusions
Thus, the result of the study was the creation of a set of equipment for accurate measurement of ultrasonic waves velocity:
- implementing several measurement methods;
- optimized to use different types of waves;
allowing to quickly change the conditions of measurement;
- enabling cross-validation of measurement results;
- accuracy of measurement of velocity less than 0.3%;
- a wide range of permissible test items such as: objects of complex shape, objects with upper and lower parallel faces and flat level surface;
- having a significant potential to expand the functionality, both in terms of measurement automation and for the development of advanced high-performance methods of non-destructive ultrasonic testing.

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