Представлено фазовий метод ультразвукової товщинометрії матеріалів зі значним загасанням та варіанти його вдосконалення з метою підвищення ефективності виявлення інформативних сигналів та точності визначення їх часового положення. Проведені комп'ютерні вимірювальні експерименти, в результаті яких обґрунтовано вибір апертури ковзного вікна в розроблених методах, отримані залежності значень сигнал/шум вихідних інформативних характеристик від значень сигнал/шум досліджуваних сигналів

Ключові слова: ультразвукова товщинометрія, фазова характеристика сигналу, перетворення Гільберта, перетворення Гільберта-Хуанга, медіанна фільтрація сигналів

Представлен фазовый метод ультразвуковой толщинометрии материалов со значительным затуханием и варианты его усовершенствования с целью повышения эффективности выявления информативных сигналов и точности определения их временного положения. Проведены компьютерные измерительные эксперименты, которые позволили обосновать выбор апертуры скользящего окна в разработанных методах, получены зависимости значений сигнал/шум выходных информативных характеристик от значений сигнал/шум исследуемых сигналов

Ключевые слова: ультразвуковая толщинометрия, фазовая характеристика сигнала, преобразование Гильберта, преобразование Гильберта-Хуанга, медианная фильтрация сигналов

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IMPROVEMENT OF THE ULTRASONIC TESTING METHOD FOR MATERIALS WITH SIGNIFICANT ATTENUATON

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1. Introduction

There is a steady tendency to extend application scope of the ultrasonic non-destructive testing (UNDT) and improve quality indicators of testing tools through the use of new information-measuring technologies. This also applies to such an important segment of UNDT as the study of composite materials. The use of methods and tools of UNDT provides information on physical and mechanical properties of a material and defects of a product.

One of the common methods of investigation of materials and products is the echo impulse ultrasonic thickness measurement (UTM) [1]. This method is based on the determination of delay τ for a passage of an ultrasonic probing signal through a test object (TO) in two directions. The expression that calculates the thickness of TO is $h=0.5v\tau$, where v is the known velocity of ultrasonic vibration in TO. Reflected signal (from an opposite surface of TO, either from defects of types of material foliation, or from product layers, which have different acoustic impedances) contains information on certain characteristics of TO. However, composite materials have a significant attenuation of ultrasonic oscillations, which complicates a process of detection and analysis of UTM, and makes it impossible to implement UNDT by existing means in some cases. Therefore, it is an important task to improve UNDT in order to increase reliability of detection of UTM signals when studying materials with significant attenuation of ultrasonic oscillations.

It is necessary to increase the power of probing signals and to increase sampling rate of a signal in analog-digital transducers in order to increase reliability of detection of UTM signals and reduce measurement errors of time intervals τ. However, practical implementation of such methods has certain limitations and is not always applicable. UTM possibilities depend not only on the way of formation of information signals in the system “ultrasonic transducer – TO”, but also on the selected informative parameters and characteristics of a signal, as well as the processing method.

2. Literature review and problem statement

An ultrasonic echo impulse method determines thickness of TO of a composite material (CM). The input/output of an ultrasonic signal to/from TO goes through combined piezoelectric transducer. Radio impulse signal carries out probing of TO. A typical model of an ultrasonic signal is a sequence of radio impulses with harmonic carrier and Gaussian envelope:

$$s_{ULT}(t)=\sum_{i=0}^{n}k_{EAP,i}\cdot s_{IMP}(t-2i\tau),\ t\in[0,T_a],\qquad (1)$$

$$s_{IMP}(t)=S(t)\cdot\sin(2\pi f_C t),\ t\in[0,\tau_{IMP}],\qquad (2)$$

where the first impulse (i=0) is the excitation impulse of an emitter, and the next ones – are reflected (or bottom) echo impulses.

In (1), (2) we indicated the following: $s_{IMP}(t)$ is the radiated radio impulse, $S(t)$ is a Gaussian pulse, τ_{IMP} is the duration of a radio impulse, f_C is the carrier frequency, $k_{EAP,i}$ is the coefficient of an electroacoustic path for the i-th impulse, $s_{ULT}(t)$ is the model of an ultrasonic signal, n is the number of impulses, τ is the time of an ultrasonic wave propagation between TO surfaces, T_a is the time interval of a signal realization. Usually, we observe a signal of ultrasonic testing against the background of additive noise:

$$s'_{ULT}(t)=s_{ULT}(t)+\xi(t),\qquad (3)$$

where $\xi(t)$ is the realization of Gaussian noise with zero mean and variance σ^2.

We can determine a signal/noise ratio at the output of a piezoelectric transducer for the i-th impulse from formula:

$$\eta=\frac{k_{EAP,i}S_{\max}}{\sigma},\qquad (4)$$

where $S_{\max}$ is the maximum value of the envelope.

Papers [1, 2] propose UTM method, which is based on using statistical phase measurement, thereafter – a basic method of statistical phase ultrasonic thickness measurement.

Basic method for detection of signals of ultrasonic thickness measurement

The method is based on the detection of bottom impulses at current values of r-statistics [1], which are determined from phase characteristics of a signal. A sample mean resultant length r, among known statistical characteristics, is the most suitable for solving a problem on signal detection and estimation of position in time. Its advantages are the invariance to the initial phase of a signal and visual graphical interpretation. A sign of the presence or absence of signal is a change in the values of phase characteristic of a signal (1), and hence the values of sample mean resultant length r, which makes it possible to detect $s_{ULT}(t)$ signals in mixture (3) even against the background of significant interference [2].

The basic method consists of the following steps:

I. We apply a discrete Hilbert transform ($\mathbf{H_D}$) to the discrete realization of signal (3) $s'_{ULT}[j]$ and obtain its Hilbert image [3] $\hat{s}_{ULT}[j]$:

$$\hat{s}_{ULT}[j]=\mathbf{H_D}(s'_{ULT}[j]),\qquad (5)$$

where $j=\overline{1,J}$, $J=T_a/T_S$, T_a is the time interval of signal realization, T_S is the UTM signal sampling period.

II. Expanded phase characteristic of a signal (PCS) are found:

$$\Phi[j]=\mathbf{K}\left(\begin{array}{l}\mathrm{arctg}\left(\dfrac{\hat{s}_{ULT}[j]}{s'_{ULT}[j]}\right)+\\ +\dfrac{\pi}{2}\left\{2-sign(\hat{s}_{ULT}[j])\cdot(1+sign(s'_{ULT}[j]))\right\}\end{array}\right),\qquad (6)$$

where $sign[]$ is the sign function, $\mathbf{K}$ is the operator of phase function deployment [3].

III. A difference $\Phi[j]$ of the phase characteristic of harmonic oscillation with the carrier frequency is found:

$$\phi[j]=\Phi[j]-2\pi f_C T_S j.\qquad (7)$$

IV. Current values of r statistics under a sliding mode during motion of a rectangular window with an aperture M_r for sample φ $[j]$ are calculated.

A sample of values at each j-th step in the case of pair M_r is analyzed:

$$\theta[k,M_r]=\left\{\phi[k],\ k\in\overline{j-\frac{M_r}{2},j+\frac{M_r}{2}},\ j\in\overline{\frac{M_r}{2},n-\frac{M_r}{2}}\right\}.\qquad (8)$$

Current value of r statistics according to expression [4] is found:

$$r[j,M_r]=\frac{1}{M_r}\sqrt{\left(\sum_{k=j-0.5M_r}^{j+0.5M_r}\cos\theta[k]\right)^2+\left(\sum_{k=j-0.5M_r}^{j+0.5M_r}\sin\theta[k]\right)^2}.\qquad (9)$$

V. Time positions of radio impulses as centers of masses q of r statistics regions are found. They correspond to echo signals and the excitation signal. The center of masses of pulses is determined from formula:

$$q=\sum_{j=k}^{m}j\cdot r[j]\Big/\sum_{j=k}^{m}r[j],\qquad (10)$$

where k and m are the values of j variable, which corresponds to the beginning and the end of an interval over which $r[j]$ statistics is investigated and is determined from condition:

$$k=j:\begin{cases}r[j+1]\le P,\\ r[j-1]>P,\end{cases}\quad m=j:\begin{cases}r[j+1]>P,\\ r[j-1]\le P.\end{cases}\qquad (11)$$

We select P value from condition that it exceeds a noise component of $r[j]$ statistics in the absence of an echo signal, for example

$$P=(\max r_{noise})\cdot k_s,\qquad (12)$$

where $\max r_{noise}$ is the maximum value of $r[j]$ statistics in regions where there is no echo signal; k_s is the safety factor, $k_s\in(1.1\div1.5)$. It is possible to make a decision on the presence of a radio impulse if $r[j, M_r]>P$.

Fig. 1 represents graphical idea of the basic method.

We used the following notation for the elements of the scheme: $\mathbf{H_D}$ is the module of discrete Hilbert transform, **PCS** is the module for PCS determination, Σ is the module of $\varphi[j]$ definition, **WP** is the module of window processing and $\theta[k,M_r]$ definition, **r** is the module for determining r statistics, **P** is the module for determining threshold P, **Q** is the module for making a decision on the presence of a radio impulse and for determining its center $q[i]$.

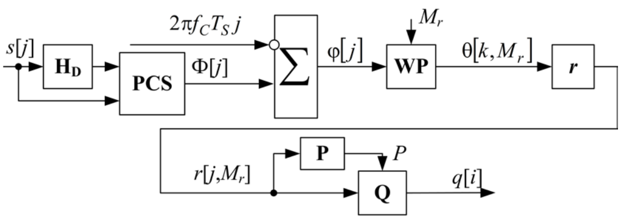


Fig. 1. Structural-logical scheme of the phase method for UTM signals detection

As it follows from formulae (10) and (12), we can conclude that it is necessary to reduce a boundary P level to extend the analysis interval in formula (10) in order to increase accuracy of determining $q[i]$. In turn, the boundary P level is proportional to the level of statistics r in the region where only a noise component of the signal is present. To reduce the level of P, it is expedient to apply additional filtering of r statistics or its weight processing.

An analysis of publications [5–10] related to UNDT showed an ever-growing interest of engineers and scientists in this testing method. For example, results of experimental studies given in paper [5] reveal a connection between the force of pressing a piezoelectric transducer and the structure of material of test object. The size of grain of the examined object, which determines attenuation of the ultrasonic wave in a material, exerts influence on the surface roughness. The Klinman's ratio, proposed in paper [5], made it possible to take into account all useful factors that are derived from a material. The authors performed studies using longitudinal waves and shear waves. These studies investigated ultrasonic structuroscopy of material.

Paper [6] reported a study into the process of ultrasonic wave analysis during their propagation in materials with significant attenuation, such as composite materials, plastics. The authors proposed using methods of deconvolution to improve detection of attenuating signals. They also suggested a discrete data model, which includes a weakening matrix in a standard convolution model. Experimental research confirmed theoretical studies, and showed the possibility to detect a signal.

Article [7] shows results of development of a device for the detection of non-invasive substances in transportation containers. The developed device uses UNDT method with advanced procedure of wave propagation and signal processing. The procedure presented in the article also provides information on the properties of a container, thickness and properties of material. The purpose of this technology is to detect hidden liquids.

Work [8] describes the Hilbert-Huang transform (HHT) as the newest method of digital signal processing. There are examples of its application in various subject areas, specifically for acoustic non-destructive testing of building structures. Paper [9] gives an example of using HHT for the detection and investigation of transient processes in passive acoustic testing. Authors of [10] proposed using HHT for ultrasonic testing for analyzing testing signals in the frequency-time domain. The use of HHT for a preliminary filtering of testing signals is not considered in detail in publications.

Thus, an overview of modern scientific developments has demonstrated a wide range of UNDT application.

Separate elements of the proposed solution are known and are employed in various subject areas, but their combination – the Hilbert-Huang transform, median filtering, analysis of circular statistics calculated by phase characteristics of cyclic signals, has not been applied to solve the tasks on detection and evaluation of signals at non-destructive testing.

Given the limitations of the basic method, as well as incomplete studies into its capabilities, and taking into consideration the prospects for improvement of its characteristics, it is necessary to propose ways to improve it in order to increase efficiency in the detection of radio impulse signals in sequence (3) and improve the accuracy of determining their time position.

3. The aim and objectives of the study

The aim of present study is to improve the basic method by expanding its capabilities for the detection of echo signals for small signal/noise relationships at the output of a transducer. This would increase the accuracy of measuring thickness of TO with significant attenuation without increasing the energy of test signals.

We set the following tasks to achieve the objective:

– to include additional operations of preliminary filtering of the investigated signals based on empirical mode decomposition and subsequent adaptive median filtering of r-statistics in the basic method;

– to use weight processing of r-statistics obtained from the analysis of phase characteristic of ultrasonic thickness measurement signal;

– to perform experimental research into basic method in order to determine its boundary possibilities and optimize values of parameters for collecting and processing the experimental data;

– to conduct experimental study of the improved methods and compare their effectiveness by analyzing the signal/noise values for initial informative characteristics of the basic method and two improved methods;

– to carry out experimental studies of the error in determining the time position of a radio impulse, detected using the basic method and two advanced methods.

4. Improvement of the basic method for detecting UTM signals

4. 1. Improved phase method for detecting UTM signals using adaptive median filtration

In order to reduce a signal/noise ratio (at which it is possible to detect echo impulses), it is expedient to include a procedure for preliminary processing of the analyzed signal and filtering of the obtained r statistics in the method of phase processing. These measures will increase noise immunity in the process of detection of echo impulses, as well as accuracy in determining their time position.

The improvement of the basic method implies the application of preliminary filtration to the investigated signal using the Hilbert-Huang transform [8] and subsequent application of adaptive median filtration to $r[j, M_r]$ [11]. The Hilbert-Huang transform makes it possible to remove significant part of the noise component from a signal at a constant time position of impulse signals (3).

The Hilbert-Huang transform consists of two stages: empirical mode decomposition (EMD) and a Hilbert analysis. The first stage implies adaptive decomposition of signal in the basis of own mode functions, which forms based on a signal analysis, that is, it is adequate to the particular investigated signal. Separated in this way, the cyclic components of signal make it possible to conduct analysis in the time and frequency-time domains.

The improved method for detecting UTM signals consists of the following steps:

I. Application to the investigated signal $s[j]$ of the method of empirical mode decomposition [8]. As a result of the initial stage, we obtain I cyclic components c_i, $i \in [1, I]$

$$c_i[j]=\mathbf{EMD}(s[j]). \tag{13}$$

The procedure for separating cyclic components is denoted by operator **EMD.**

II. Preliminary filtration is the restoration of signal of ultrasonic testing by the part of defined cyclic components:

$$s_v[j]=\sum_{i\in K} c_i[j], \tag{14}$$

where K is the set of indexes of selected cyclic components. We discard cyclic components according to the level relative to a noise component or a trend. Such a procedure makes it possible, for example, to exclude the noise and other non-informative components of signal from consideration.

III. A discrete Hilbert transform for the modified restored signal $s_v[j]$ is performed:

$$\hat{s}_v[j]=\mathbf{H_D}(s_v[j]). \tag{15}$$

IV. We define $\Phi_v[j]$ and $r_v[j, M_r]$ for $s_v[j]$ and its Hilbert-image $\hat{s}_v[j]$ according to (6), (9).

V. We use a method of adaptive median filtration (AMF) for the obtained statistic characteristic – the sample mean resultant length $r_v[j, M_r]$ (SRVL). Underlying the AMF method is the sliding median filtering of signals. We improved the median filtration method by a dynamic change in the aperture of a sliding window, which makes it possible to achieve a compromise between the requirement for the undistorted impulse transmission and a significant reduction in the dispersion of noise [11].

AMF operator indicates the filtering operation:

$$r_f[j,M_r]=\mathbf{AMF}(r_v[j,M_r]). \tag{16}$$

VI. We apply a threshold **P** function (12) to the filtered sample mean resultant length $r_f[j,M_r]$ vector and find centers of impulses (10).

Fig. 2 shows graphical representation of the improved phase method for detecting UTM signals using EMD and adaptive median filtration.

We used the following notation for the elements of the scheme: **EMD** is the module of empirical mode decomposition, **CF** is the module for selection of informative components and restoration of UTM signal, $\mathbf{H_D}$ is the module for the discrete Hilbert transform, **PCS** is the PSC determination module, Σ is the module for determining $\varphi[j]$, **WP** is the module of window processing and determination of $\theta[k, M_r]$, **r** is the module for determining r statistics, **AMF** is the module of adaptive median filtering of r statistics, **P** is the module for determining the threshold P value, **Q** is the module for decision making on the radio impulse presence and determining its center $q[i]$.

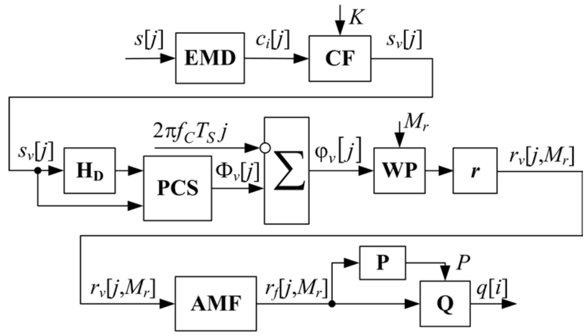


Fig. 2. Structural-logical scheme of the improved phase method for detecting UMT signals using EMD and adaptive median filtration

4. 2. Improved phase method for detecting UMT signals using the weight processing of r statistics

Another option for improving the basic method of phase ultrasonic thickness measurement is the additional processing of r statistics multiplying it by its weight function. Weight function must be adapted to r statistics. Thereafter, such a variant of the improvement of the basic method is termed as "phase method for detecting UMT signals using a weight function".

The phase method for detecting UMT signals using a weight function consists of the following steps:

I. We apply the basic method for detecting UTM signals (5)–(9) to the discrete implementation of signal (3) $s'_{ULT}[j]$ and obtain $r[j]$ statistics.

II. We calculate current values of a sample standard deviation of r statistics in the sliding regime while moving a rectangular window relative to sample $r[j]$.

We determine $r[j]$ at each j-th step from analysis of the sample:

$$\theta_\sigma[k,M_r]= =\left\{\phi[k],\ k\in\overline{j-\frac{M_\sigma}{2},j+\frac{M_\sigma}{2}},\ j\in\overline{\frac{M_\sigma}{2},n-\frac{M_\sigma}{2}}\right\}. \tag{17}$$

The current value of the sample standard deviation of r statistics is determined in accordance with expression:

$$\hat{\sigma}_r[j,M_\sigma]=\sqrt{\frac{1}{M_\sigma-1}\sum_{k=j-(M_\sigma-1)/2}^{j+(M_\sigma-1)/2}\left(r[k]-\overline{r}_j\right)^2}, \tag{18}$$

where $\overline{r}_j$ is the average value of the sample, formed by window WP2.

III. Current values of weighted statistics r_{WT} are derived from expression:

$$r_{WT}[j]=r[j]\hat{\sigma}_r[j]. \tag{19}$$

IV. Based on weighted statistics $r_{WT}[j]$, a P threshold (12) and impulse centers are determined (10).

Fig. 3 shows a generalized structural-logical scheme of the improved phase method for detecting UTM signals using a weight function.

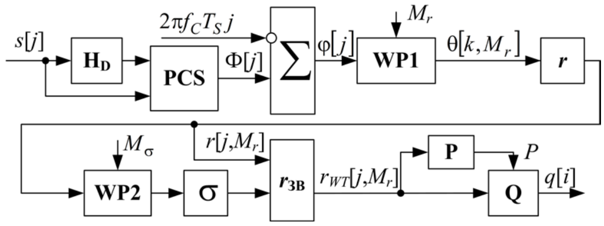


Fig. 3. Structural-logical scheme of the phase method for detecting UMT signals using a weight function

We used the following notation for the elements of the scheme: $\mathbf{H_D}$ is the module of the discrete Hilbert transform, **PCS** is the PSC determination module, ∑ is the module for determining $\varphi[j]$, **WP1, WP2** are the modules of window processing, **r** is the module for determining r statistics, **σ** is the module for determining a sample standard deviation of r statistics, $\mathbf{r_{WT}}$ is the module for determining the weighted r statistics, **P** is the module for determining a threshold P value, **Q** is the module for decision making on the presence of a radio impulse and for determining its center $q[i]$.

5. Statement of the problem on modeling and analysis of the results

We conducted computer simulation experiments to comprehensively compare the basic and the improved methods for detecting UTM signals.

We divided model experiments into two main groups:

1) study of the influence of M_r size on the noise component of r statistics in the basic method for detecting UTM signals;

2) estimation of feasibility of the basic and improved methods for detecting UMT signals for different values of signal/noise ratio at the output of a transducer and examination of the dependence of error in the determination of time position of the detected echo-impulses on the value of signal/noise ratio at the output of a transducer.

Experimental study to detect the influence of size M_r of aperture of the sliding window on a noise component of r statistics for the basic method for detecting UTM signals.

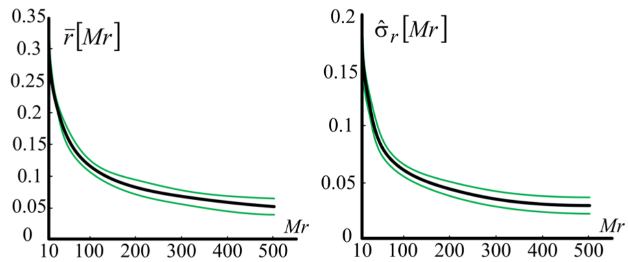
The study was performed for the Gaussian noise at zero mean and a variance equal to 1. We apply the basic method for detecting UTM signal to the investigated signal and determine r-statistics for the obtained implementation of PCS of noise signal for various M_r values in the range from 10 to 500 points with a step of 1. We compute the estimation of mean ($\bar{r}[Mr]$) and the standard deviation ($\hat{\sigma}_r[M_r]$) in r-statistics for each aperture value.

In order to improve reliability of modeling, the estimation of values $\bar{r}[Mr]$ and $\hat{\sigma}_r[M_r]$ was performed on a sample of size 100, that is, on 100 different implementations of the noise signal with the same parameters. Fig. 4 shows dependence charts of the estimates of mean and the standard deviation in parameter $\bar{r}[Mr]$ ($MEAN_{\bar{r}[Mr]}$ and $STD_{\bar{r}[Mr]}$, respectively) and parameter $\hat{\sigma}_r[M_r]$ ($MEAN_{\hat{\sigma}r[Mr]}$ and $STD_{\hat{\sigma}r[Mr]}$, respectively) on the aperture of a sliding window.

Based on an analysis of the obtained charts, it is possible to draw the following conclusions:

– there is a general tendency to a decrease in the values of r statistics for the noise component with an increase in aperture of the window;

– for the case when aperture increases from 10 to 150 counts, the mean value of r statistics decreases approximately from 0.32 to 0.1. Further increase in the aperture does not lead to a significant decrease in the mean value of r statistics, therefore, it can be considered impractical.



a *b*

Fig. 4. Dependence charts of the estimation of parameters on the aperture of a sliding window: *a* – parameter $\bar{r}[Mr]$ (black line – $MEAN_{\hat{\sigma}r[Mr]}$, green lines – $MEAN_{\hat{\sigma}r[Mr]} \pm 3STD_{\hat{\sigma}r[Mr]}$); *b* – parameter $\hat{\sigma}_r[M_r]$ (black line – $MEAN_{\hat{\sigma}r[Mr]}$, green lines – $MEAN_{\hat{\sigma}r[Mr]} \pm 3STD_{\hat{\sigma}r[Mr]}$)

We conducted experimental study to estimate feasibility of the basic and the improved methods for detecting UTM signals at different signal/noise values at the output of a transducer. We also investigated dependence of the error in determining a time position of the detected echo impulses on the signal/noise value at the output of a transducer.

To assess efficiency of the advanced methods for detecting UTM signals, computerized measurement experiments were performed to analyze dependence of the signal/noise ratio of r (η_{out}) statistics on the signal/noise ratio of the input signal (η_{in}). We compared results for the basic and for two improved methods.

We selected a model of ultrasonic testing as a model of the analyzed signal. In the discrete realization, it takes the following form:

$$s[j] = s_{RI}[j] + S_B s_{RI}[j - Nt_2] + n[j] \quad j = \overline{1, J}, \tag{20}$$

$$s_{RI}[j] = S_G[j]\sin(2\pi f_C j T_S), \tag{21}$$

where $s_{RI}[j]$ is the implementation of a radio impulse with a gaussian envelope and carrier frequency f_C, $S_B \in [0, 1)$ is the amplitude of an echo impulse, $S_G[j]$ is the Gaussian envelope of a radio impulse, $n[j]$ are the samples of Gaussian noise with zero mean and variance σ^2, Nt_2 is the time position of an echo impulse. We considered a model with one reflected radio impulse. Signal/noise ratio $s[j]$ for the section of an echo impulse is $\eta_{in} = S_B^2/\sigma^2$.

The following groups of experiments were performed to identify and analyze limitations in the examined methods:

1. Investigation of dependence $\eta_{out}(\eta_{in})$ and the aperture value of sliding window M_r for the basic method for detecting UTM signals, and substantiation of M_r value for conducting further experiments.

2. Investigation of dependence $\eta_{out}(\eta_{in})$ for the basic and two improved methods.

3. Investigation of dependence of the error in determining time position of the received echo impulse on η_{in} for the basic and for two improved methods.

A general procedure for conducting tests for the first two groups of experiments included the following:

1. We formed arrays of values for parameters of the investigated magnitudes ($\eta_{in}[k]$, $M_r[k]$).

2. Simulation parameters are determined.

3. We determined dependences $\eta_{out}(\eta_{in}[k])$ and $\eta_{out}(M_r[k])$.

3. 1. We formed the investigated signal $s[j]$ according to the established modeling parameters and assigned values of ($\eta_{in}[k]$, $M_r[k]$).

3. 2. We applied the basic method and two improved UMT methods to the formed signal and determined r statistics for each method.

3. 3. We found η_{out} values for the echo signal for the determined r statistics using expression:

$$\eta_{out} = \left(r[j, M_r]_{\max} - \overline{r}\right) / \hat{\sigma}_r, \qquad (22)$$

where $r[j, M_r]_{\max}$ is the maximum value of r statistics for the echo signal, $\overline{r}$ is the mean value of r statistics in sections where there are no echo signals, $\hat{\sigma}_r$ is the estimation of standard deviation in r statistics in the absence of echo signals.

3. 4. We repeated steps 3.1–3.3 for each value from the array of parameters (η_{in}, M_r) and formed the output array of values for the dependence of the investigated parameter $\eta_{out}[k]$ on $\eta_{in}[k]$, $M_r[k]$.

4. We repeated point 3 for each η_{in}, M_r parameter and obtained dependence arrays $\eta_{out}(\eta_{in})$, $\eta_{out}(M_r)$ for the basic method and two improved UTM methods.

The procedure for studying a dependence of the error in determining a time position of the received echo impulse on η_{in} included the following:

1. An array of values $\eta_{in}[k]$ is formed.

2. Simulation parameters are determined.

3. We determined dependence $\Delta_q(\eta_{in}[k])$.

3. 1. We formed the investigated signal $s[j]$ according to the established modeling parameters for the assigned value of $\eta_{in}[k]$.

3. 2. We applied the basic method and the improved UTM methods to $s[j]$ and determined r statistics for each of them.

3. 3. We found the value of center (q) of the echo impulse for the determined r statistics using expression (10).

3. 4. The error in determining a time position of the echo impulse is found:

$$\Delta_q = |q - Nt_2|, \qquad (23)$$

where Nt_2 is the time position of echo impulse assigned in modeling.

3. 5. We repeated points 3.1–3.3 for all $\eta_{in}[k]$ values and formed the output array of values $\Delta_q[k](\eta_{in}[k])$ for the basic method and the improved UTM methods.

The following parameters were chosen for (20):

– amplitude of the Gaussian envelope S_G=1V;

– signal sampling rate f_S=50 MHz;

– frequency of the carrier of radio impulse signal f_C= =1 MHz;

– amplitude of echo impulse S_B=0.15 V;

– time of signal observation T_A=200 μs;

– duration of radio impulse τ_{imp}=6 μs, or 300 counts;

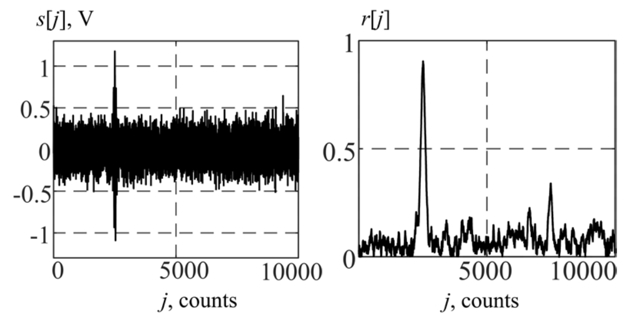
– time position of the center of radio impulse of excitation t_1=50 μs, or Nt_1=2,500th count;

– time position of the center of echo impulse t_2=150 μs, or Nt_2=7,500th count;

– sample size J=10,000;

– range of the investigated values of parameters: $\eta_{in}\in[0,02, 10]$ $M_r\in[100, 500]$.

The experiments were repeated 100 times to increase the reliability of results; the obtained r statistics were averaged. A given statistical approach can be proposed not only for computer simulation, but also for field experiments with actual TO. Fig. 5 shows charts of the investigated signal (η_{in}=1) and the r statistics derived for it.



a *b*

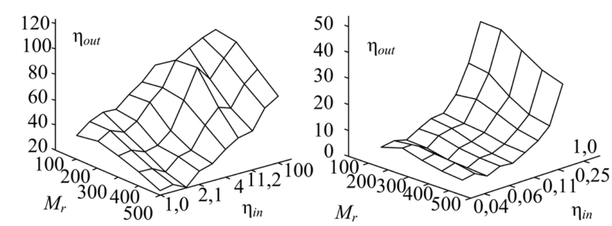
Fig. 5. Charts: *a* — the investigated signal; *b* — *r*-statistics of the investigated signal

Based on analysis of the value and shape of r statistics, we can conclude that the echo impulse is located in the vicinity of the time count j=7,500, which cannot be achieved by analyzing the envelope of the signal (Fig. 5, *a*).

5. 1. Results of examining a dependence $\eta_4(\eta_{in}, M_r)$ for the basic method for detecting UTM signals

Fig. 6 shows results of experiments obtained using the above procedure.

To ensure high level of testing reliability, it is appropriate to choose a threshold P level under condition $\eta_{out}\geq 6$. Fig. 6, *b* shows that the detection of UMT signals under the accepted assumptions (the accumulation of signal implementations and the averaging of the obtained r statistics) for η_{in}>0.2 proceeds without errors.



a *b*

Fig. 6. Dependence $\eta_{out}(\eta_{in}, M_r)$: *a* — for η_{in}>1; *b* — for $\eta_{in}\leq 11$

The charts obtained make it possible to substantiate the choice of M_r value for the assigned values of η_{out}, η_{in}: $M_r=0.5\cdot\tau_{IMP}\cdot f_C$=150.

5. 2. Results of examining a dependence $\eta_{out}(\eta_{in})$ for the basic method and the improved UTM methods

The experiments were carried out at $\eta_{in}\in[0,02, 2]$. We accepted other parameters to be equal to basic conditions.

Fig. 7 shows in the form of charts results of the experiments carried out using the proposed method.

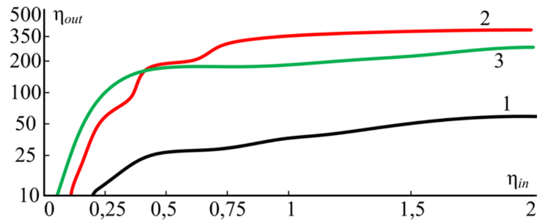


Fig. 7. Dependence $\eta_{out}(\eta_{in})$ for: 1 – basic UTM method; 2 – method that employed a weight function; 3 – method that applied adaptive median filtering

The ratio of η_{out} for the improved methods is almost an order of magnitude higher than the respective η_{out} values for the basic method for detecting UTM signals. In addition, the results obtained indicate that:

– the method for detecting UTM signals using adaptive median filtering could be applied to process signals at $\eta_{in} \geq 0.08$;

– the method for detecting UTM signals employing weight functions could be used to process signals at $\eta_{in} \geq 0.1$.

5. 3. Comparison of errors in determining a time position of the detected impulses using the presented methods

Results of the study are shown in Fig. 8 in the form of dependence charts of $\Delta_q(\eta_{in})$ for the basic method and the improved methods.

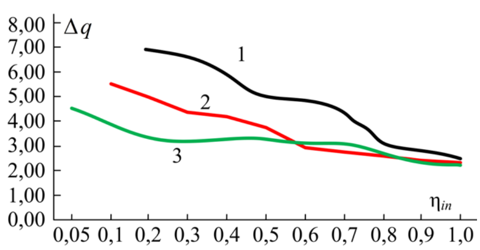


Fig. 8. Dependence $\Delta_q(\eta_{in})$ for: 1 – basic UTM method; 2 – method using a weight function; 3 – method employing adaptive median filtering

Fig. 8 allows us to conclude that the improved UTM methods ensure a 1.5–2 decrease in the error of determining a time position of echo impulses and enable performance in the range of signal/noise ratio, extended towards lower values, – to $\eta_{in} \geq 0.8$.

6. Discussion of results of testing the improved methods of ultrasonic thickness measurement

It is proposed to improve a known ultrasonic method of non-destructive testing taking into consideration the latest trends in the use of composite materials in various fields of science and technology and the need to test their quality. Improvement of the phase method of echo impulse thickness measurement involved two ways:

– the use of a combination of procedures of preliminary filtration of the investigated signals based on empirical mode decomposition and subsequent adaptive median filtering of *r*-statistics;

– the application of weight processing of *r*-statistics.

In general, modeling of the processes of UTM signals processing by the improved methods showed an increase in accuracy and noise immunity. This effect is achieved, however, at the expense of significant complication of the algorithm for processing experimental data.

The results obtained could be used for the development of new precision ultrasonic echo impulse thickness measurement devices with improved metrological characteristics. Such devices would be capable of testing the thickness of articles made from materials with a significant attenuation of ultrasonic oscillations.

Further research on the developed method to test materials with significant attenuation should be directed to the application in ultrasonic defectoscopy. However, it should be taken into consideration that at the low levels of signals from defects, the latter will be disguised as a reverberation obstacle. It is required to search for the attributes that would make it possible to separate these components of the signal.

7. Conclusions

1. Presented study considers improvement in the accuracy of measurement of thickness of TO with significant attenuation. We proposed the improvement to the phase method of echo impulse thickness measurement in two ways: using a combination of procedures of preliminary filtration of the investigated signals based on empirical mode decomposition and subsequent adaptive median filtering of *r*-statistics, and applying weight processing of *r*-statistics.

2. We experimentally investigated the basic method in order to determine its boundary capacity, as well as to substantiate values of its parameters. We established the necessity to align the aperture of window M_r for sliding determination of *r* statistics and the length of radio impulse of the testing signal. Under the assigned modeling conditions, the largest inhibition of random component in the control signal occurs when $M_r=0.5 \cdot \tau_{IMP} \cdot f_C$.

3. We studied experimentally the improved methods and compared their efficiency by analyzing the signal/noise values for initial informative characteristics of the basic method and two improved methods. Results of the performed experiments prove that the UTM method that employs adaptive median filtering, in contrast to the basic one, could be used for signal analysis at $\eta_{in} \geq 0.08$; the method that utilizes weight functions – at $\eta_{in} \geq 0.1$.

4. We experimentally investigated the error in determining a time position of the radio impulse detected using the basic method and two improved methods: the error in determining a time position of the detected echo impulses, when applying the improved methods, is 1.5–2 times less than the error when the basic method is used.

5. An analysis of the results of modeling indicates the higher efficiency of the presented improved UTM methods; however, for values $0.5 \geq \eta_{in} \geq 0.08$, it is more appropriate to use the method that employs adaptive median filtration, and for $\eta_{in}<0.5$ – the method that involves weight functions. Therefore, it is expedient to combine the improved methods.

References

1. Kuts Yu., Shcherbak L. Statistical phasometry. Ternopil, 2009. 383 p.
2. Lapiga I. Circular statistics application for accuracy improvement of ultrasonic thickness measurement // “Proceedings of IX Conference Polit-2009”. Kyiv: NAU, 2009. P. 60.
3. King F. W. Table of selected Hilbert transforms // Hilbert Transforms. Cambridge: Cambridge University Press, 2009. P. 453–533. doi: 10.1017/cbo9780511735271.011
4. Bendat J. S., Piersol A. G. Random Data: Analysis and Measurement Procedures. 4th ed. Hoboken: John Wiley & Sons, Inc., 2010. 640 p. doi: 10.1002/9781118032428
5. High Frequency Ultrasonic Non Destructive Evaluation of Additively Manufactured Components / Karthik N., Gu H., Pal D., Starr T., Stucker B. // 24th Annual Int. Solid Freeform Fabr. Austin, TX, 2013. P. 311–325.
6. Including frequency-dependent attenuation for the deconvolution of ultrasonic signals / Carcreff E., Bourguignon S., Idier J., Simon L., Duclos A. // Proceedings of Meetings on Acoustics. 2013. Vol. 19, Issue 1. P. 055029. doi: 10.1121/1.4800850
7. Tucker B. J., Diaz A. A., Eckenrode B. A. Advanced ultrasonic measurement methodology for non-invasive interrogation and identification of fluids in sealed containers // Nonintrusive Inspection, Structures Monitoring, and Smart Systems for Homeland Security. 2006. doi: 10.1117/12.660439
8. Hilbert-Huang transform and its Applications / N. E. Huang, S. S. P. Shen (Eds.). CRC press, 2005. 324 p. doi: 10.1142/9789812703347
9. The Hilbert-Huang transform in Engineering / N. E. Huang, N. O. Attoh-Okine (Eds.). CRC Press, 2005. 328 p. doi: 10.1201/9781420027532
10. Lu Y., Oruklu E., Saniie J. Application of Hilbert-Huang transform for ultrasonic nondestructive evaluation // 2008 IEEE Ultrasonics Symposium. 2008. doi: 10.1109/ultsym.2008.0365
11. Derhunov O., Kuts Yu. Sposib adaptyvnoi mediannoi filtratsiyi impulsnykh syhnaliv: Pat. No. 103513 UA. MPK G06F 7/02 / zaiavnyk ta patentovlasnyk Nats. aviats. un-t. No. u201504262; declareted: 30.04.2015; published: 25.12.2015, Bul. No. 24.

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ITERATIVE HARD-DECISION DECODING OF COMBINED CYCLIC CODES

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Пропонуються циклічні коди, що ітеративно декодуються, і які можна розглядати як альтернативу турбо-кодам та LDPC-кодам. Ці коди основані на каскадному поєднанні двох різних циклічних кодів Хеммінга. Для (n, k)-коду виправляються всі помилки кратності до (n–k). Кодова швидкість ИДЦК наближається до одиниці з ростом довжини коду. Використовуються тільки жорсткі рішення, завдяки чому досягається висока швидкодія та проста апаратно-програмна реалізація кодера і декодера

Ключові слова: ітеративне декодування, циклічні коди, коди Хеммінга, лінійна послідовнісна схема, перемежування

Предлагаются итеративно декодируемые циклические коды (ИДЦК), которые можно рассматривать как альтернативу турбо-кодам и LDPC-кодам. Эти коды основаны на каскадном соединении двух различных циклических кодов Хэмминга. Для (n, k)-кода исправляются все ошибки кратности до (n–k). Кодовая скорость ИДЦК приближается к единице с ростом длины кода. Используются только жесткие решения, благодаря чему достигается высокое быстродействие и простая аппаратно-программная реализация кодера и декодера

Ключевые слова: итеративное декодирование, циклические коды, коды Хэмминга, линейная последовательностная схема, перемежение

1. Introduction

The vast majority of error correction codes, which are widely applied at present, were developed in the 50’s and 60’s of the last century, immediately after the publication of the seminal paper by C. Shannon on coding theory [1]. These codes did not require any sophisticated algorithms for transforms, which is why they were relatively easily implemented. The only exception was the low-density parity-check (LDPC) codes: the level of development of computer technology in those years did not allow their implementation [2].

Over the following decades, the theory of error correction coding evolved and developed without much innovation. The next significant achievement was the invention of turbo codes [3]. The key innovation to these codes was the idea of iterative decoding, which, in a slightly different