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The Use of Complex-Modulated Signals at US Testing of Extended Complex-Structured Products

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Abstract

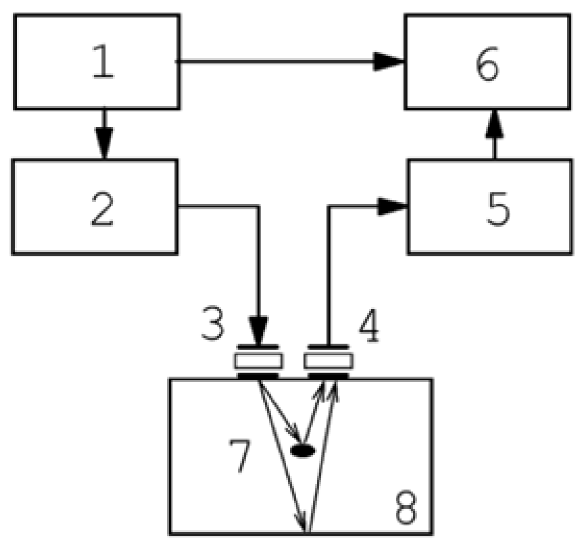
The results of analysis of the possibilities to use Complex-Modulated radio pulses as probing signals in US flaw detection are given. It is shown that the application of Complex-Modulated echo signals in the receiving path optimal filters improves the basic parameters of the echo control method – sensitivity and resolution capability, and, in presence of white noise and not correlated interference, generally increases the reliability of the testing method.

Keywords: Complex-Modulated Signals, Electro acoustic Pickup, Frequency-Modulated Pulse, Optimal Filtering, Phase-Shift Keyed Signal, US Flaw Detection

1. Introduction

The location principle, as a method of detection and measurement of coordinates of objects in space, is put in the basis of both the radio locator and US echo pulse flaw detector. The structural scheme of an active US locator is simple. Synchronizer[1] (Figure 1a) activates the generator[2], which generates a short electrical pulse (Figure 1b) exciting the radiating piezoelectric transducer[3] (RPT). RPT[3] forms in the testing product[7] acoustic probing pulses. This method of generating a short probing US (US) pulse is called the "shock excitation" method. Reflected from the defect[7] and from the bottom of product[8], US echo signals are recorded by input piezoelectric transducer (IPT)[4] and after boosting by the input amplifier[5] come to the input of the indicator (I)[6]. The arrival time of the echo pulses allows judging about the depth of the defects, and the amplitude of the echo pulses is determined by the sizes of the defects (Figure 1b).

In subsequent years, systematic studies to optimize the structure of radar aids for improving their energy potential, resolution capacity and accuracy of definition of coordinates, development of methods of noise immunity of radar stations and other, based on the use of radar systems of wideband and ultra-wideband probing signals, noise-like probing signals and methods for their optimal filtering were conducted.



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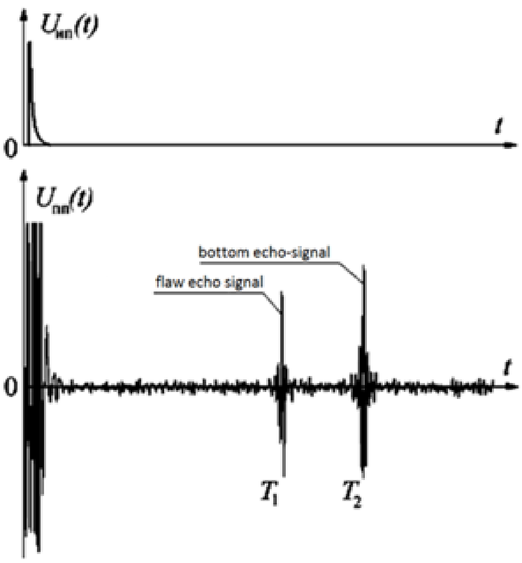


(b)

Figure 1. a -structural diagram of USecho pulse flaw detector; b - time diagrams of echo pulse flaw detector according to the "shock excitation"method.
USecho pulse control according to the "shock excitation"method.

Along with these achievements, US flaw detection cannot boast such a big success. Up to the present time the algorithm of "shock excitation" is a basis of almost all-modern flaw detection equipment carrying out control at High Frequency (HF) US spectrum (1 MHz to 10 MHz or more). This is explained by the fact that among the structural materials metals most widely applicable, and as is known, the attenuation of US waves in metals is relatively small, the spectral distortion is negligible and therefore traditional equipment provides satisfactory practical result.

The feature of traditional algorithm of "shock excitation" is that the parameters of the US probing pulses (pulse amplitude, mean frequency f_o, duration T_c, radiation directivity) are determined by the parameters of the used Piezoelectric Transducers (RPT). The average frequency of the US signal f_o is determined by the resonant frequency of the RPT, and the length T_c is determined by the transmission band Δf_n of RPT.

High resolution is achieved if the duration of the probing signal is equal to the duration of 2 to 3 periods of the carrier frequency. Practically decrease of the probing pulse duration is achieved by mechanical damping of RPT that expands the RPT transmission band. However, damping reduces the amplitude of the US signal and reduces the sensitivity control.

Single-channel scheme of the US control with shock excitation of US signals (Figure 1a) is the main scheme for the vast majority of traditional instruments US NDT. Along with the obvious advantage of its simplicity, it has obvious drawbacks. The scheme can generate only one type of signal; it does not allow changing quickly and smoothly the parameters of probing signals; the received signals in the receiving path are exposed to minimal radio technical processing. For this reason, over the years of development of US flaw detection methods and means, the qualitative changes did not occur, and modernization of the equipment fleet consisted, as a rule, only of extension of the set of service functions, improving the display quality of the flaw detection information. The only achievement of modernization is the appearing opportunity of forming the probing radio pulse signal of the adjusted length in a digital way. The reason is that, on the one hand, the traditional means of US NDT provide satisfactory control of the vast majority of products and structures made of metal, and, on the other hand, the implementation of promising ideas and creation of NDT new means is limited by the national Standards, guidelines, methods existing in various sectors.[1]

2. Problems of US Testing of Large Complex-Structured Products with a Large Attenuation of US Inspection

However, this trend in the development of US NDT methods and means developed over the decades was broken with appearance of large-sized products from Polymeric Composite Materials (PCM), control of which using the traditional equipment with shock excitation of the probing signals was difficult to realize. However, as experience shows, the variety of PCM products involves the development of an original method of control for each new product with a definite set of parameters of the probing signal and processing algorithms of echo pulses, which is practically difficult to implement in a deterministic, not variational scheme with shock excitation of the probing signal. The similar problems were arising previously when testing large construction concrete products with complex heterogeneous structure[2] and excessively high ultrasound attenuation, however, the task of PCM products control initiated development of new noise-immune methods of US non-destructive testing in our research group.

The control problem for products with large attenuation of US testing is illustrated by the block diagram shown in Figure 2.

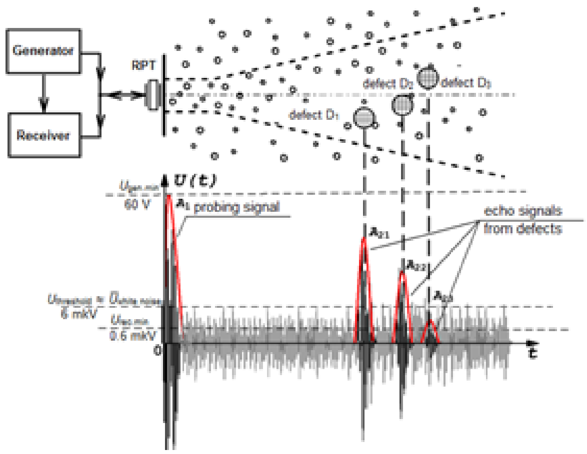


Figure 2. Diagram of the echo pulse control of the extended complex-structured product.

Reflected from defects D_1, D_2, D_3 echo signals A_{21}, A_{22}, A_{23} attenuate considerably and according to the amplitude become comparable to the amplitude of limit value threshold defined by white noise voltage $U_{lev} \approx U_{white\,noise}$ of the receiving path of flaw detector. It is obvious that each compound structure material has its acoustic characteristics, but the common factor is that in complex-structured materials there is a strong attenuation of the US inspection not only due to the absorption of US waves, but due to their scattering on structural heterogeneities. Moreover, if their sizes are comparable with the length λ of the US wave, there is a lot of reflection, which together forms a "Structural Noise" (SN) masking and distorting echo signals from defects.

In the situation shown in Figure 2b, the amplitude of the structural noise does not exceed the amplitude of the echo signals A_{21}, A_{22}, A_{23} and does not mask them. The amplitude of the received US echo signal A_2 depends on the amplitude of the probing signal A_1 and properties of the controlled material determined by the attenuation rate $\delta(f)$, as well as the magnitude of the controlled thickness X:

$$A_2 = A_1 \cdot \exp(-\delta(f)\,X). \qquad (1)$$

Indicator of integral attenuation $\delta(f)$ [dB/m] is determined by two different processes: absorption $\delta_{погл}(f)$ and dissipation $\delta_{расс}(f)$ of the US oscillations on the structural heterogeneities of the material[1]:

$$\delta(f) = \delta_{погл}(f) + \delta_{расс}(f) = \alpha f^{m} \beta f^{n} (\bar{D})^{k} \qquad (2)$$

Where $\check{D}$ is an average size of structural heterogeneities, α, β, m, n, k are constants depending on the acoustic properties of the environment.

The higher the frequency of the US wave, the greater the attenuation of the US signal is, which for concrete is illustrated by shown in Figure 3 frequency dependence $\delta(f)$ of attenuation rate δ.[1] The similar dependence $\delta(f)$ graph can be constructed for Polymer Composite Materials (PCM).

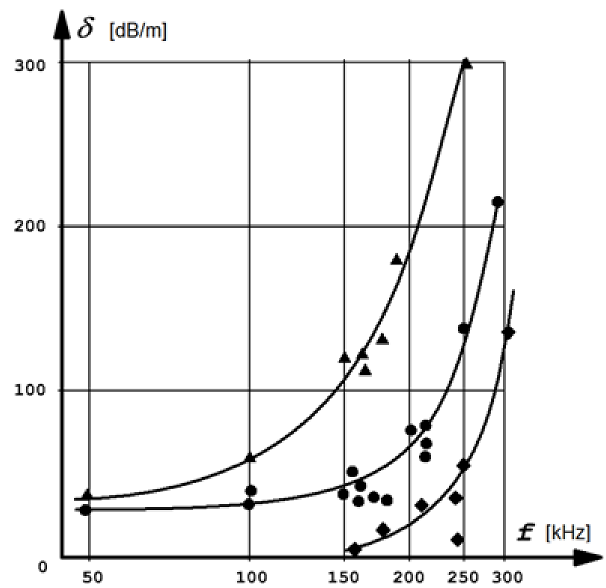


Figure 3. Generalized frequency dependence of the attenuation factor of US waves for concrete with different filling aggregates: 1 - granite filler with average size of $\bar{D} \approx 10\,mm$; $\bar{D} \approx 20\,mm$ (granite) ; $\bar{D} \approx 20\,mm$ (limestone).

If complex structured concrete products or PCM are of great length, the ultrasound attenuation is so large that the amplitude of the echo signals becomes comparable with the noise level of the input circuits of the US flaw detector receiving path (as shown in Figure 2 for echo signal A_{23}).

Developers of US equipment seek to increase the sensitivity of the monitoring equipment, i.e. to be able to detect the US echo signals similar to the signal A_{23} reflected from defect[3]. In the framework of the traditional US NDT methods, implementation of this one is possible only by increasing the efficiency of electro acoustic transducers or by increasing the amplitude $U_{ген}$ of probing signal A_1. However, these methods of increasing sensitivity are limited to the maximum possible amplitude of the electrical signal $U_{ген} = U_{1max}$ applied to the radiating transducer.

To increase sensitivity more efficiently, it is possible reducing the frequency of the probing signal[1], as this reduces the value of attenuation rate $\delta (f)$. Therefore, the US control of large products of complex-structured materials (concrete, PCM) is carried out at frequencies of about 100 kHz and below. However, when reducing the frequency of the probing signal, there is a big problem with increasing the wavelength of the US oscillation. Because of this length of the US probing pulse T_c (in concrete at the frequency $f_0 \approx 100$ kHz, the length of one oscillation period T_0 is 40 mm) increases and thereby radial resolution capability is impaired $Dx=CT_c/2$. Therefore, to ensure the highest possible resolution, duration of the probing pulse should not exceed 1-2 periods of the carrier frequency, which in turn implies using of broadband piezoelectric transducers with the transmission band $Df_{пп}$, corresponding to the width of the signal spectrum: $Df_{пп} \approx Df_c$. Here it should be noted that it is difficult enough to provide transmission band of the piezoelectric transducer $Df_{пп} \approx 100$ kHz at frequency of 100 kHz without loss of sensitivity. In addition, the increase in the duration of the probing pulse leads to an increase in errors in the determination of the time delay of the echo signal $Dt_з$, i.e. the increase of error DX in measurement of thickness X of the product. In[3] it is shown that the relative error in the thickness measurement DX/X is determined by the relative error DC/C of speed measurement C of US oscillation in the monitored object of control and relative error Dt_c/T_c of the signal temporal position measuring: $DX/X= DC/C + Dt_з/t_з$. Since the values of measurement errors of speed and delay time are roughly the same, it can be assumed that $DX/X \approx 2Dt_з/t_з$. In other words, the accuracy of product thickness measuring is determined by the accuracy of determining the temporal position of the echo signal.

The error DX exists during thickness measurement of metal products. However, in the MHz range due to the relatively short duration of the US probing signal, the error DX is not so great. At lower signal frequency up to 100 kHz (30 to 50 times), the same increase is in absolute values of the errors DX and $Dt_з$. For this reason, when carrying out LF testing it is necessary to pay special attention to the value of the error $Dt_з$ and carefully choose the method and means to measure the value of the echo signal delay time.

When performing the low-frequency control the echo signal shape has a significant impact on the error value, as the echo signal is distorted in electro-acoustic path both during propagation in complex-structured products and due to the distorted shape of the amplitude-frequency characteristics of LF broadband piezoelectric transducer.[4]

Thus, the problem of US inspection of extended complex-structured products required the solution of several tasks:

- creating the means for extraction of echo signals from the white noise,
- providing high resolution improving the measuring accuracy of the delay time of echo signals,
- creating easily tunable apparatus adaptable to changing control conditions of various properties of the products.

Thus, the successful solving of such a multifactorial problem occurs only if the comprehensive implementation of the following tasks:

- use certain types of Complex-Modulated (CM) signals as probing ones;
- apply a variety of radio-technical processing and filtering the echo signals;
- develop an adaptive multi-functional means of US control, which provides the user with the potential for each class of products to adapt easily the parameters of US control equipment for characteristics of the controlled product.

The research group of MPEI has developed integrated solutions for US inspection of large materials with a large attenuation of ultrasound and complex heterogeneous structure for more than 40 years, which proposed to use accumulation of periodic signals[5] for extracting echo signals from white noise as far back as the 60s; and later Complex Modulated (CM) signals (Linear Frequency Modulated (LFM) and Phase-Shift Keyed (PSK) signals, known from radar broadband, providing both extraction of echo signals from the defects out of white noise and high resolution capability[6,7], were proposed for use in US flaw detection.

3. Ways and Methods for Increasing Sensitivity of the Us Inspection of Large Products with Great Attenuation of US Signals

The problem of extracting echo signals from white noise is solved in the theory of optimal filtering of signals generated in the radiolocation. This problem can be easily adapted to the specific tasks of US inspection of extended products, since the formulation of the echo signal detection problem in the US flaw detection is similar to the radiolocation task: unknown is the fact of presence or absence of the echo signal (echo signals) $V_1(t)$ in the received oscillation $U_1(t) = V_n(t)$, as well as the amplitude and its (their) delay time. Very weak US echo signal $V_1(t)$ is also masked by white noise – noise of the receiving part of the US flaw detector. However, the US echo signal in contrast to radar signal undergoes a stronger distortion in the electro acoustic path.

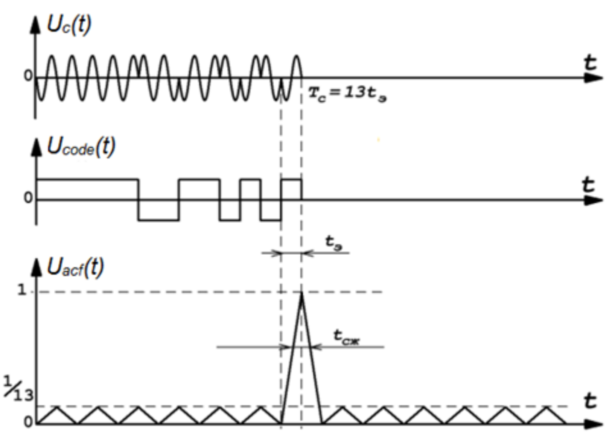
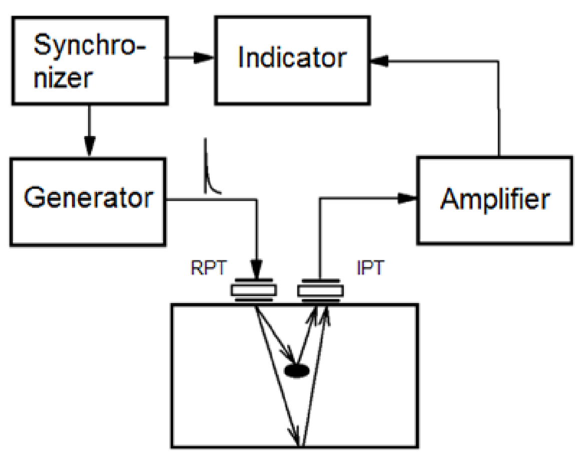


Figure 4. Barker's phase-shift keyed signal N=13, corresponding to it video code and autocorrelation function of Barker videocode.

Similar problems involved in radiolocation and US flaw detection and vast experience in solving the problems of noise-immune signal reception in radiolocation allowed using achievements of optimal filtering in US NDT, the essence of which is that the mixture of the echo signals from defects with the signal noise is applied to the filter input consistent with the signal that in the best possible way ensures the extraction of the echo signal from the defect out of the noise maximizing the of signal/noise value. According to the optimal filtering theory, at the definite value of the white noise N_0 and the signal energy $E_1=(V_1)^2T_c$ the signal/noise ratio value at the output of the optimal filter consistent with the echo signal is the maximum possible proportional $\frac{2E}{N_0}$, and at the final amplitude of the probing signal $V_1(t)$ it can be increased only by increasing duration of the T_c signal. These provisions of the theory of optimal signal filtering determine the requirements for the probing US signals and algorithms of their processing.

3.1 The Requirement for the Signals Used in Noise-Immune US Flaw Detection.

When used as a component of the US flaw detector of the optimal filter, the signal at the output of the receiving path (on the detector indicator) is not an echo signal enhanced by amplitude, and is described by the Auto Correlation Function (ACF) of the echo signal. In addition, the longer duration of the probing signal is, the greater the amplitude of the maximum of ACF of the signal at the OF output is. It is obvious that for the problem of echo-location it is desirable to choose the type of complex modulated probing signal according to the form of the autocorrelation function – not just "high-energy" signal, but such one in which ACF is formed by one main maximum. This condition corresponds to the known in radiolocation high-energy, long time Frequency-Modulated (FM) and Phase-Shift Keyed (PSK) signals, which optimal filtering operation compresses them in time with the formation of short maximum duration $t_{сж} \ll T_c$ at low level of side lobes and increases their amplitude (Figure 4). The use of such complex-modulated signals simultaneously provides high sensitivity and the resolving ability of the control.



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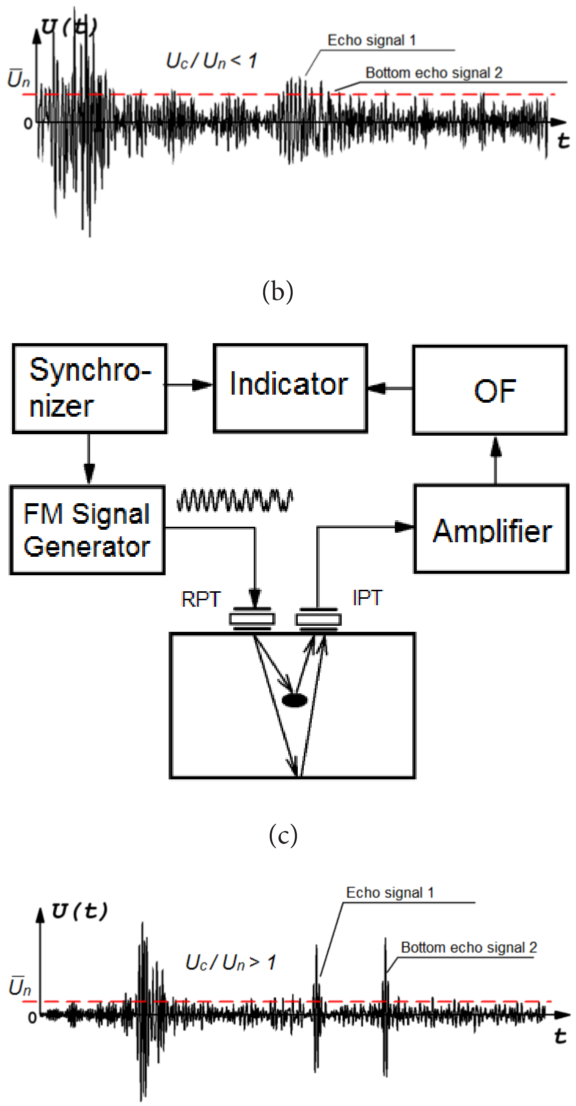


(b)

(c)

(d)

Figure 5. Application of the CM signal to increase sensitivity and resolution

In MPEI in 1974, the first article considering the use of FM signals in US flaw detection was published.[8] Now CM signals and their optimal filtering are widely used in the US testing equipment, but, unfortunately, they are not used in an integrated manner, rather to solve a practical problem – increasing the sensitivity of control.[9,10].

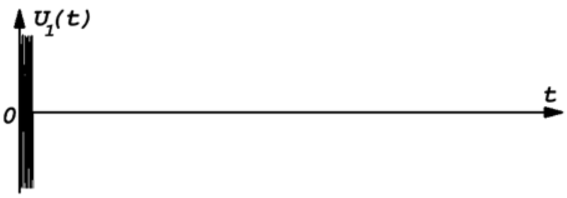
Figure 5 shows comparison of the structural scheme of the detectors and the Oscillograms of their operation demonstration the simultaneous increase of sensitivity and radial resolution capability of echo-control due to use of CM signals as probing ones and optimal filtering of the echo signals. When radiating in large-sized product with large integral attenuation of the pulse excitation (Figure 5a), US waves are attenuated so much that echo signals, reflected from located nearby defects, are not distinguished on the background of white noise, because their amplitudes are less than the level of noise $U_{порог} = U_{ш}$. In addition, these echo signals are not resolved in time (Figure 5a). Figure 5 shows that during radiation of long probing US FM signal in the controlled product, after OF the recorded echo signals are shortened and resolved in time, and due to increasing the amplitude of the main lobe are distinguished from noise (Figure 5d). The temporal position of the echo signals is fixed according to the position of the maxima of the compressed pulses.

3.2. Properties of CM Signals Applied to the Problems of US Testing of Products Made of Materials with High Attenuation of Ultrasound.

The main property of CM signals is the ability to increase the control sensitivity by changing parameters of the probing pulse. Thus, Figure 2 shows that when the amplitude of the US echo signal A23 is 0.6 μv at the level of the white noise N_o=const = 6 μv, for reliable detection of the echo signal A_{23} on the background of white noise when using the impulse excitation method, it is necessary to increase the probing signal amplitude by more than 10 times. However, it is impossible to increase the probing signal amplitude infinitely. The length of the probing signal is limited by the requirements for the resolution of the US testing. When CM signals are used as probing ones, due to the optimum filtering of the echo, signal-to-noise ratio increases by $Б = (T_c/t_{сж})^{½}$ times.

If the maximum dynamic range of a traditional US pulse-echo flaw detector with impulse excitation of the probing signal is 140 dB, the use of CM signals with large databases increases it by additional 40 - 50dB.

The results of the CM signal application for increasing the US testing sensitivity are shown in Figure 6. When measuring the concrete block thickness, the LFM signal (Figure 6a) with frequency deviation in the range from 50 to 150 kHz with a relatively short duration of the signal T_{c1} and, respectively, with a small base $Б_1 = \Delta f_c\ T_{c1}$, was used. However, when this value of the base signal $Б_1$, the amplitude of compressed LFM signal is low and the reflection from the bottom of the concrete product is identified unreliable (Figure 6b). (Here it should be noted that the measurement of a temporal position of the echo signal in this example is made from the moment defined by a compressed signal of Electro Acoustic Pickup (EAP), which, in turn, corresponds to the end of the probing LFM signal).



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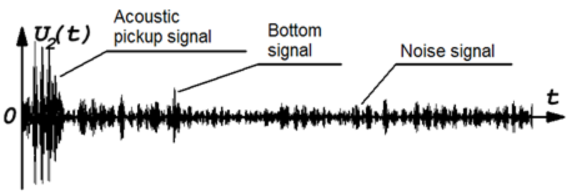

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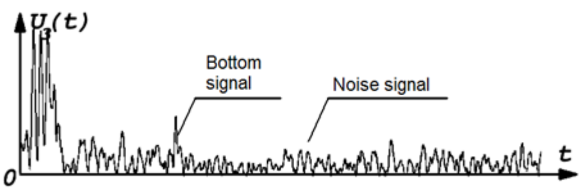

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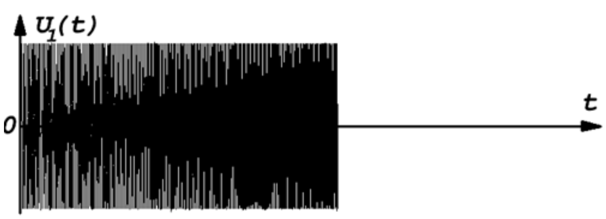

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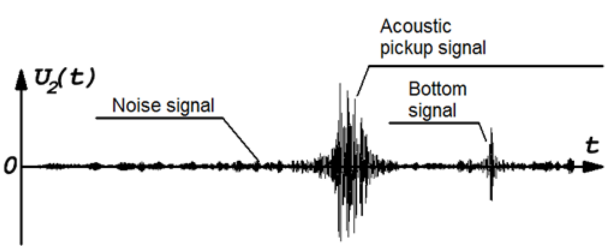

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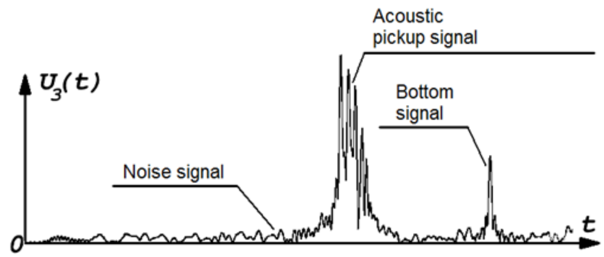


(f)

Figure 6. The increase of the sensitivity control due to increasing base of the probing LFM signal
a -probing LFM signal with base Б1 =Δfc Tc1; b -LFM signal with base Б1 after optimal filtering; c-LFMsignal with base Б1after optimal filtering and synchronous detector; d - sounding LFM signal with base Б2 =ΔfcTc2; e - LFM signal with baseБ2after optimal filtering; f - LFM signal with base Б2 after optimal filtering and synchronous detector.

To increase the sensitivity in the control process, the value of base $Б_2$ of the probing LFM signal was increased due to increase in the pulse duration up to value T_{c2} (Figure 6d). Accordingly, EAP signal was shifted to the right along the time axis and the point of reference for determining the time delay of the bottom signal was shifted. Due to increase in the signal duration (and base *Б*), the signal-to-noise ratio was increased, enabling to register reliably and measure the time delay of the bottom echo signal (Figure 6e).

Optimal filtering of CM signal can improve not only the sensitivity, but also the accuracy of the echo signal time delay measurement. The task of accurate determination the echo signal time delay in presence of white noise is a statistical problem, it is therefore necessary to use statistical methods for its solving. The radio metering theory shows that minimized value of dispersion measurement error of echo signal time delay can be recorded[10]:

$$\sigma^2 t \min \sim \frac{1}{\left(\frac{2E}{N_0} . \Delta F_c^2\right)} \quad (3)$$

Where: $\frac{2E}{N_0}$ - the maximum signal/noise ratio at the output of the optimal filter; ΔF_c - width of the signal spectrum.

Thus, potential accuracy of the temporal position measurement of the echo signal is higher when the signal/noise ratio is larger and range of the signal is wider. As can be seen from[3], a necessary condition for achieving the minimum measurement error of the echo signal delay time is to maximize the signal/noise ratio and use of broadband probing signal. In other words, to ensure high accuracy measurement, broadband high-energy complex modulated signals with subsequent optimal filtering of the echo signals in the receiving path should be used as probing ones.

Table 1 - Table 4 present the results of mathematical modeling of delay measurements of optimally filtered LFM echo signal at different values of its base under the same white noise (before and after the synchronous detector).

Table 1. The results of 20 measurements of echo signal delay at the output of the optimal filter (signal duration T_{c1} = 250 μs, the signal/noise (S/N) ratio at output of the optimal T_{c1} filter S/N = 14 dB)

No measurement	delay (μs)	No measurement	delay (μs)	No measurement	delay (μs)	No measurement	delay (μs)
1	250.0	6	249.7	11	249.9	16	250.3
2	250.3	7	250.1	12	250.4	17	250.0
3	249.7	8	249.4	13	249.9	18	250.6
4	250.0	9	249.7	14	249.9	19	249.8
5	250.3	10	249.3	15	249.5	20	250.0

The LFM signal with medium frequency F_c = 100 kHz, frequency deviation dF = 100 kHz and duration T_{c1} = 250 μs and T_{c2} = 1 ms was used as a probing signal in the calculations. The delay of the echo signal was chosen to be equal $t_{31} = t_{32}$ = 250 μs. To assess the impact of the synchronous detection operation, measurements were carried out both at the output of the optimal filter (upstream the synchronous detector) and at the output of the synchronous detector. Changing the duration of the probing signal enabled to change its base and, thereby, the value of the signal/noise ratio. As expected, the increase of the sensitivity of US testing due to the increased base of the probing signal allows measuring delay of the echo signal more accurately. Thus, fourfold increase of the base results in the measurement error reduction by almost 30%; however, the synchronous detection increases the inaccuracy almost twice. It should be noted that for large values bases of the probing signal and, accordingly, substantial excess of the amplitude of the echo signal in the average level of noise (20 dB or more) loss of precision is almost negligible.

Table 2. The delay measurement results of the optimally filtered echo signal at the output of the synchronous detector (signal duration Tc1 = 250 μs, the S/N ratio at the output of the optimal filter S/N = 14 dB)

No measurement	delay (μs)	No measurement	delay (μs)	No measurement	delay (μs)	No measurement	delay (μs)
1	249.5	6	249	11	249.9	16	250.8
2	250.3	7	252.4	12	249.2	17	249.0
3	249.8	8	250.1	13	249.3	18	249.2
4	249.9	9	249.6	14	250.9	19	250.2
5	250.5	10	250.2	15	250	20	249.4

Table 3. The delay measurement results of the optimally filtered echo signal at the output of the synchronous detector (signal duration Tc2 = 1 ms, the S/N ratio at the output of the optimal filter S/N = 6 dB)

No measurement	delay (μs)	No measurement	delay (μs)	No measurement	delay (μs)	No measurement	delay (μs)
1	249.2	6	249.4	11	249.2	16	249.6
2	250.1	7	250	12	249.9	17	250.1
3	250.2	8	249.6	13	250.1	18	249.6
4	249.8	9	250.1	14	250.8	19	250.7
5	249.7	10	250.1	15	250.3	20	249.9

Analyzing the results shown in Table 5, we can conclude that at presence of noise, increase in the base B of the Complex-Modulated probing signal increases the accuracy of the echo signal delay measurement.

3.3. Use of the Complex-Modulated Signals for Increasing the Resolution Capability of the US Control.

Simultaneously with the increase in sensitivity, using the CM signals can improve radial resolution capability of the US echo testing.

Table 4. The delay measurement results of the echo signal at the output of the optimal filter (signal duration Tc2 = 1 ms, the S/N ratio at the output of the optimal filter S/N = 6 dB)

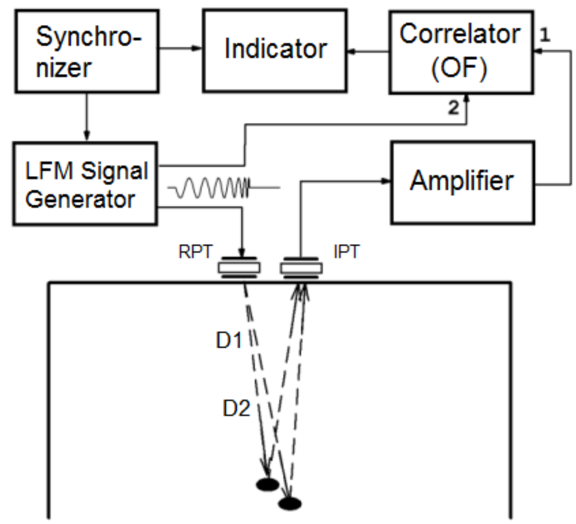
No measurement	delay (µs)	No measurement	delay (µs)	No measurement	delay (µs)	No measurement	delay (µs)
1	249.2	6	249.4	11	249.2	16	249.6
2	250.1	7	250.0	12	249.9	17	250.1
3	250.2	8	249.6	13	250.1	18	249.6
4	249.8	9	250.1	14	250.8	19	250.7
5	249.7	10	250.1	15	250.3	20	249.9

Table 5. The dependence of the expectation values M and mean square deviation σ for the measured values of the time delay of the echo signal from the base value B of the probing signal and the type of mathematical processing of the echo signal.

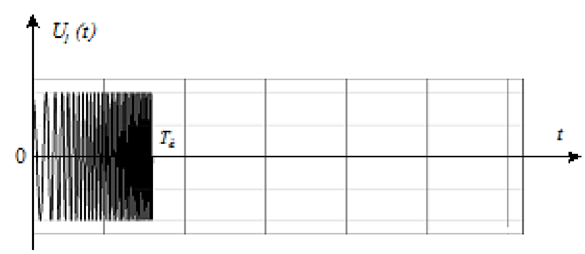
Signal base B	S/N (dB)	Operations	M [µs]	σ [µs]
100	14	OF	249.94	0.329
		OF and SD	249.96	0.781
25	6	OF	249.92	0.415
		OF and SD	250.015	0.979

Echo signals reflected from nearby defects of large-size product (Figure 7c) are not registered on the background of white noise and uncorrelated interference, because their amplitude is below the noise level of input circuits of the receiving path; these echo signals are not resolved in time. After optimal filtering, "compressed" signals are resolved in time and due to increasing signal/noise ratio are detected in the background noise (Figure 7d).

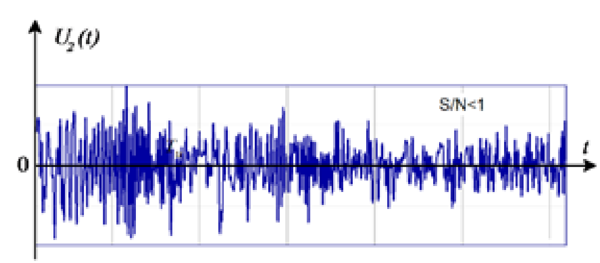
Using Complex-Modulated signals as probing pulses and integration of the optimal filter according to the correlator diagram with the receiving path, changed the detector block diagram. In comparison with the structural diagram of the traditional US pulse-echo flaw detector with pulse excitation of the probing signal (Figure 1a) in the diagram shown in Figure 7a it is necessary to supply the reference signal from the LFM signal generator to the second input of the receiving path correlator to implement the optimal filtering operation of the received LFM echo signal.



(a)

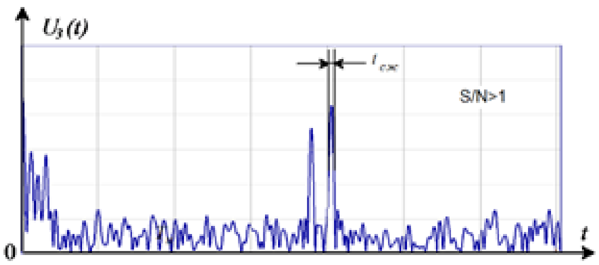


(b)



(c)

Such a scheme of US flaw detector structure is more complicated than the traditional pulse excitation forming scheme, however, it allows changing quickly and efficiently the parameters of the probing signal (medium frequency F_c, width of the spectrum Δf_c, signal duration T_c) in the course of US testing, which significantly extends its capabilities.



(d)

Figure 7. a -control circuit; b–probing LFM signal; c - USLFM echo signals masked by the white noise; d - echo signals after OF and a synchronous detection

US inspection using the LFM signal

4. US Multifunctional Measuring System.

Structural diagram of the US flaw detector depicted in Figure 7 allows using only one of the many Complex-Modulated signals – LFM signal and one kind of radio-technical processing – optimal filtering (compression) of this LFM signal. The next step in the improvement of US NDT equipment was the creation of the universal hardware-software Measurement Complex (MC), enabling to generate various types of simple and complex-modulated signals algorithmically and programmatically, to implement any algorithms for radio-technical processing of the US echo signals, to use multiplex control of the products including with US phased antenna arrays used (Figure 8).

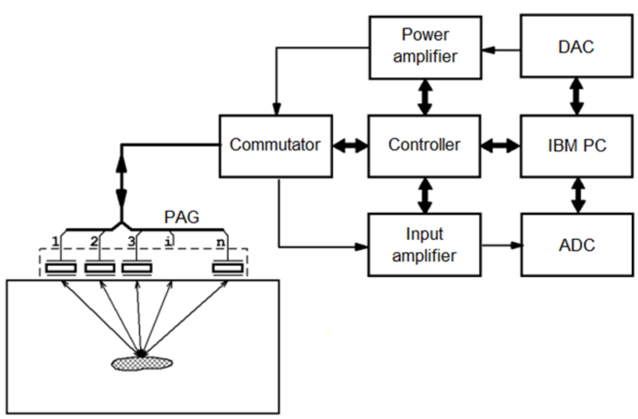
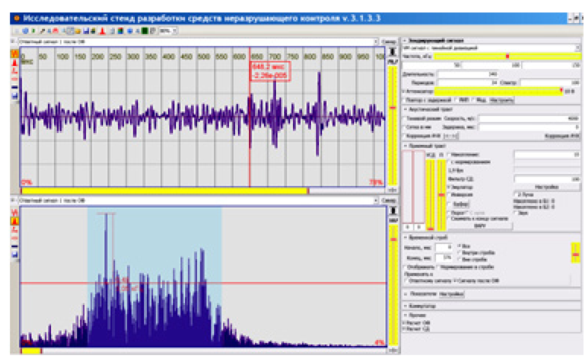


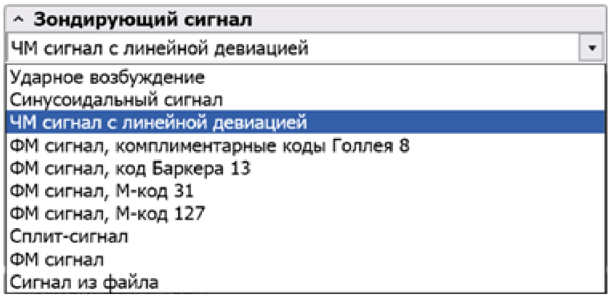
Figure 8. Structural diagram of hardware-software multifunctional adaptive complex of noise-immuneUS flaw detection

In the multifunctional MC, formation of complex-modulated signals is carried out by hardware, and the choice of their parameters is implemented programmatically. The interface panel of the hardware-software complex "Research stand for development of nondestructive inspection aids" is shown in Figure 9a. The type of the probing signal is selected on the drop-down panel "Probing signal" in the setting region (Figure 9b), where some "basic" signals are: 1. "Pulse excitation" – a short pulse of positive or negative polarity with adjustable duration and amplitude; 2. "Sinusoidal signal" – a radio pulse envelope of rectangular, Gaussian or arbitrary shape with adjustable duration, frequency and amplitude; 3. LFM signal – a radio pulse with carrier frequency varying according to linear law of the envelope having rectangular, Gaussian or arbitrary shape with adjustable duration, medium frequency, deviations, and amplitude; 4. PSK complementary Golay signals with index N=8; 5. PSK Barker signal 13; 6. PSK M-signal with index N=127; 7) Split-signal. Individual parameters of each of the signals are operatively configured by the operator on the setting control panel of the probing signal (the panel for the LFM signal is shown in Figure 9c).



(a)

(b)



(c)

Figure 9. a - theinterface panelof the hardware-software complex; b - the list of available types of the probing signal; c - the setting control panel of the probing signal.
Hardware-software complex "Research stand of development of nondestructive inspection aids"

5. Conclusion

Use of high-energy complex-modulated signals with good correlation properties as probing, as well as application of algorithms for spatio-temporal and optimal filtering allowed us to design and create the modern hardware-software complex for low-frequency US non-destructive inspection of large-size products with a unique opportunity for rapid, parametric, algorithmic adaptation to the properties of the controlled objects. In the next articles, some of the original features of the software-hardware complex that enable both to modify the well-known algorithms of US non-destructive inspection[12] and to create and implement new ones will be discussed.

6. Acknowledgments

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