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GENERAL ASPECTS OF NONDESTRUCTIVE INSPECTION

The Synthesized Video-Signal Method in Nondestructive-Testing Problems

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Abstract—A method based on a proposed echolocation diagnostic technique (RF Patent 2446407 dated 27.03.2012) can be efficient for detecting both single and multiple defects with a sufficiently high accuracy, is described with a view to the development of diagnostic equipment. The essence of the method is the use of a probing signal composed by sequentially formed harmonic oscillations at several different frequencies, and a joint processing of received reflected signals.

Keywords: synthesized signal, diagnosed cable, fault location of transmission and communication lines, reflection factor, dispersion, weighting function

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INTRODUCTION

Echo-location methods, which are based on the principle of the detection of reflected waves, have gained wide application in different nondestructive radio wave and acoustic testing problems [1–3]. Different versions of their implementation are known, but they differ in both the types and methods of forming probing signals (amplitude, frequency, and phase) and the processing algorithm for the received reflected signals. In spite of significant achievements in the nondestructive testing area, the work on upgrading the equipment for echo-location, acoustic, and radio-wave diagnostics of materials and products continues. The important factors of echo-location diagnostic facilities include the detection ranges of defects, the evaluation accuracy of their location, and resolution. As one of lines of designing equipment with improved technical indices, the approach based on the idea of synthesizing a video-pulse signal, which is close in sense to the method that is used in radiolocation for probing terrestrial covers, has been proposed [4]. The possibility of using the above method in nondestructive-testing problems is considered in this paper.

1. THE SYNTHESIZED VIDEO-SIGNAL METHOD

The essence of this method consists in the fact that the probing signal is radiated as quasi-continuous oscillations at several different frequencies. The received reflected signal is subjected to complex weighted summation, ensuring the formation of small-duration video pulses. The above processing is the artificial synthesis of the video-pulse signal from physically existing harmonic co-components. As applied to nondestructive-testing problems, it is possible to use this method at least in two aspects.

The first of these is the use of the principle of synthesis in one-dimensional echo-location problems. Similar problems are characteristic of the echo-location control of lengthy linear objects, e.g., radio-wave control of different cable transmission and communication lines. In these cases, electromagnetic waves of some different frequencies are excited in the wave-guiding structure and the total reflection coefficient from existing irregularities is detected (Fig. 1).

In the case of a single irregularity with the reflection coefficient $\Gamma_0(\omega)$, the measured reflection coefficient is equal to:

$$\Gamma_{in}(\omega) = \Gamma_0(\omega)e^{-2jx_0(\beta(\omega)+j\alpha(\omega))}, \qquad (1)$$

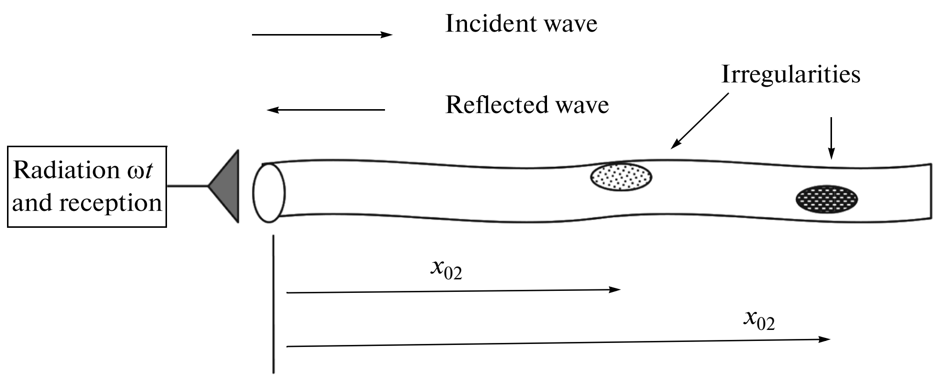

Fig. 1. A cable communication line with two irregularities. The one-dimensional case.

where $\beta(\omega)$ and $\alpha(\omega)$ are the phase and attenuation coefficients of the wave in the structure. The received signal is subjected to weighted processing in accordance with the rule:

$$U(x) = \left|\int_{\omega_1}^{\omega_2} \Gamma_{in}(\omega, x_0) K(\omega, x) d\omega\right|. \quad (2)$$

In the base version we use the weighting function, whose argument can be written as:

$$\arg K(\omega, x) = 2j\beta(\omega, x) \quad (3)$$

In this case, the synthesized signal $U(x)$ is the pulse function, which main maximum is reached at the value x, which is equal to the distance to the physically existing irregularity. In the presence of several irregularities two or more *peaks* of $U(x)$ that correspond to irregularities are observed. As an illustration, the calculated dependences for the radio-wave diagnostics of a cable communication line are shown in Fig. 2.

The second aspects is the use of the principle of synthesizing video pulses in testing or diagnostic problems of volumetric or planar objects. In these cases, the probing signal is also a set of harmonic oscillations. Waves in the volume of the object are created at each frequency and the excitation of propagating waves and the reception of reflected waves from boundaries of the object and irregularities is carried out by the corresponding converter (antenna) (Fig. 3).

In the simplest case, when a single point irregularity occurs, the reflection coefficient at frequency ω is equal to:

$$\Gamma_{in}(\omega, r_0) = C(\theta, \varphi, \omega)\frac{e^{-2jr_0(\beta(\omega) + j\alpha(\omega))}}{r_0^2}, \quad (4)$$

where r_0 is the range to the irregularity and $C(\theta, \varphi, \omega)$ is a value that is determined by the directional and frequency properties of the conversion unit (antenna).

The received reflected signals were processed similarly to one-dimensional echo location, but in combination with the spatial scanning of the antenna. As a result, the video signal synthesis ensures the range selection and the angular directional properties of the converters (antennas) ensure the ability to separate the observations of reflecting properties in angular coordinates. Figure 4 shows the calculated dependences of the observed intensity of the synthesized video-pulse signal for the model case of two point irregularities in an unbounded medium.

The synthesized video-signal method admits some modifications, which allow one to substantially improve the technical indices of echo-location diagnostic units. All modifications are based on the fact that the selection of the weighting function $K(\omega)$ in the form of the constant (in absolute value) value $|K(\omega)| = \text{const}$ is not the only possible choice. The use of weighting functions of different types, which represent an additional degree of freedom, opens wide possibilities for improving the detection characteristics, measurements, and the recognition of defect types. These possibilities show themselves especially brightly during the echo-location of lengthy one-dimensional structures. Some possibilities are represented below based on the example of echo-location radio-wave diagnostics of cable transmission and communication lines.

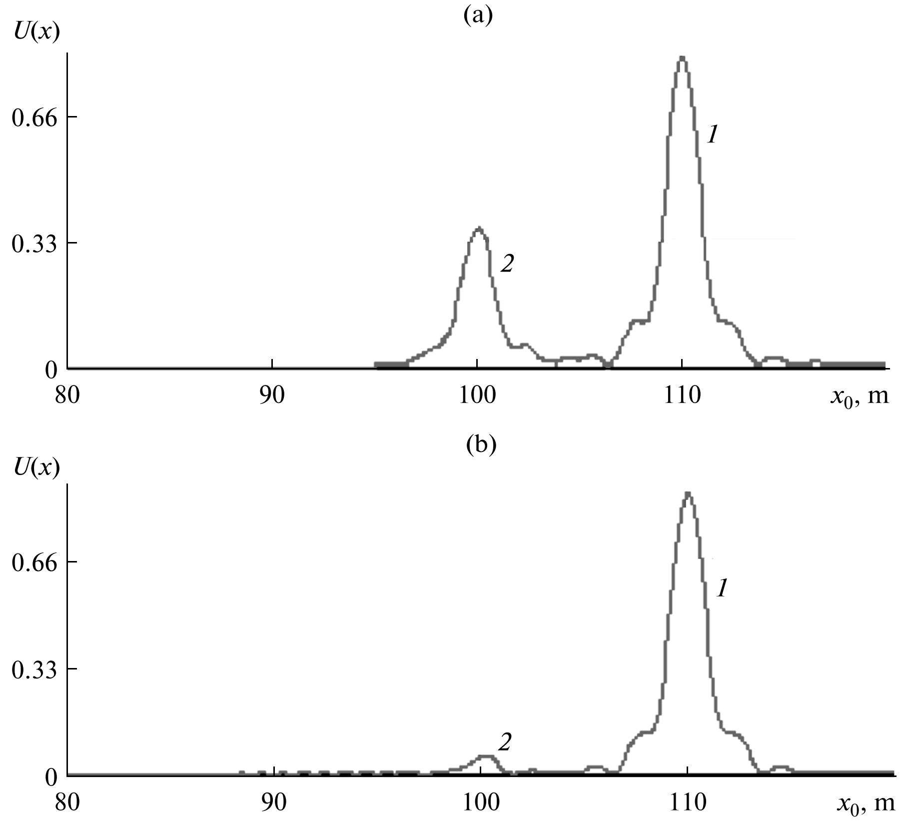

Fig. 2. The dependence of the normalized $U(x)$ for the case with two irregularities: (*1*) a break at a distance of 110 m; (*2*) unauthorized branching of the main line at a distance of 100 m. The branching is represented by the equivalent scheme with different resistances: (a) $Z = 75\ \Omega$; (b) $Z = 750\ \Omega$ and $Z_0 = 75\ \Omega$. The signal-to-noise ratio = ∞.

2. AN INCREASE IN THE TECHNICAL CHARACTERISTICS OF DIAGNOSTIC UNITS OF CABLE DEFECTS BY THE SYNTHESIZED VIDEO-PULSE METHOD

The technical coefficients of the existing diagnostic facilities of cable communication lines do not always meet the desired requirements. The drawbacks of the typical pulse reflectometers include the insufficient reliability of detection of some types of defects *dead areas*, accuracy and resolution that are not always satisfactory, and the deterioration of qualitative indices in the process of diagnosing long lines due to the influence of losses and dispersion in the cable. These circumstances stimulate the continuation of efforts on upgrading the above-mentioned facilities [7–14]. In this respect, the use of the synthesized video-signal method [15–16] opens very wide possibilities for improving qualitative coefficients. Let us demonstrate the most important of them.

2.1. Compensation of the Influence of Losses in Transmission Lines and Dispersion

The compensation of losses and distortions due to dispersion is carried out using the weighting function $K(\omega) = e^{2\alpha(\omega)x}/e^{j2\omega x}/V\text{ph}(\omega)$, where $\alpha(\omega)$ and $V\text{ph}(\omega)$ are the known frequency dependencies of the attenuation coefficient and phase velocity in the transmission line. In this case, the width of the *peak* and its position on the axis of ranges do not depend on the location of the irregularity (Fig. 5). The collateral effect of this compensation is the reduction in the signal/noise ratio for the synthesized signal.

2.2. Reduction in the Side-Lobe Level

The drawbacks of the base version of video-signal synthesis with the weighting function $K(\omega)$ = const include a high side lobe level (secondary local maxima that surround the region of maximal values, $U(x)$, at the location of the irregularity, x_0). These lobes feature a strongly pronounced character at small distances to the defect and small attenuation in the transmission line, and, as the distance to the irregularity (or attenuation in the transmission line) increases, their *swelling* occurs, with the preservation of the level

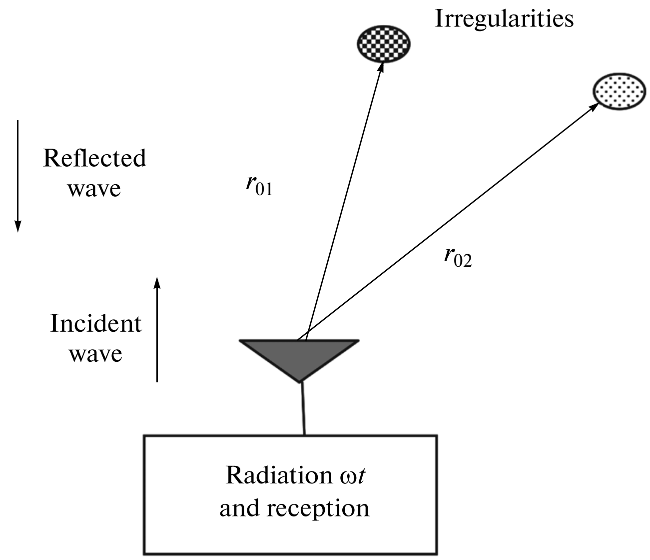

Fig. 3. Synthesizing the video pulse in the three-dimensional case with two irregularities.

on average. This phenomenon is well seen in Figs. 2 and 5. The presence of side lobes in the structure of the synthesized signal has the drawback that they can mask poorly reflecting irregularities, whose positions correspond to the side-lobe area. It is possible to substantially reduce them by purposively selecting the weighting function $K(\omega)$. In fact, in the absence of attenuation the structure of expression (2) is the Fourier transform of the function $K(\omega)$). As is well known, Fourier transforms with lengthier basic *peak* regions but lower side lobes correspond to functions that decay to the edges. The exponential multiplier in expression (1) does not lead at the qualitative level to a change in this property. Therefore, by selecting the weighting function in the appropriate form [17], it is possible to substantially decrease the side lobe levels of the synthesized signal and, thus, their negative effects. The data that are given in Fig. 6 can act as an illustration.

A decrease in the synthesized signal amplitude and an increase in its width are the inevitable consequences of the reduction of the side lobes. Therefore, if it is necessity, the issue of the optimal function $K(\omega)$ that is selected from the criterion of the *width to side lobe level* ratio can be dealt with in a similar manner to that in the theory of linear antennas [17].

2.3. The Increase in the Detection Range of Inhomogeneities

It is known that as the distance to an inhomogeneity increases, the widening of the $U(x)$ *peak* occurs, i.e., an increase in the shift relative to the true position of the inhomogeneity due to the dispersion influence and, most substantially, a decrease in the maximal amplitude of $U(x)$ (see Fig. 5). When the power of the signal oscillator is fixed, the range of the detected inhomogeneity is limited by the intrinsic noise of the receiver. The qualitative character of the processes that are related to the detection of the signal from noise and the methods that are directed at reducing their influence are similar to those that have been well studied in the theory of radio reception, in particular, for radio location applications [5–6].

Thus, with a unit amplitude of the incident wave and the fixed noise level of the input unit, the maximum reachable detection range x_{max} is determined by exceeding the detection threshold $U(x_{max}, \alpha(\omega_0)) = U_{thr}(\omega_0, N_{ns})$ by the absolute value $|U(x_0)|$. As is well known, the maximum signal/noise ratio is reached in a linear receiver on the condition of the optimal filtering; the use of the weighting function $K_2(\omega) = \text{const}e^{-\alpha(\omega)x}$ corresponds to this fact. On the condition that the processing is optimal, the maximally reachable detection range of the inhomogineity with the unit reflection coefficient is limited by the values of the frequency band $(\omega_2 - \omega_1)$, the attenuation coefficient in the transmission line $\alpha(\omega_0)$, and the noise level (sensitivity) of the receiver. As an illustration, the possible detection region is shown in Fig. 7.

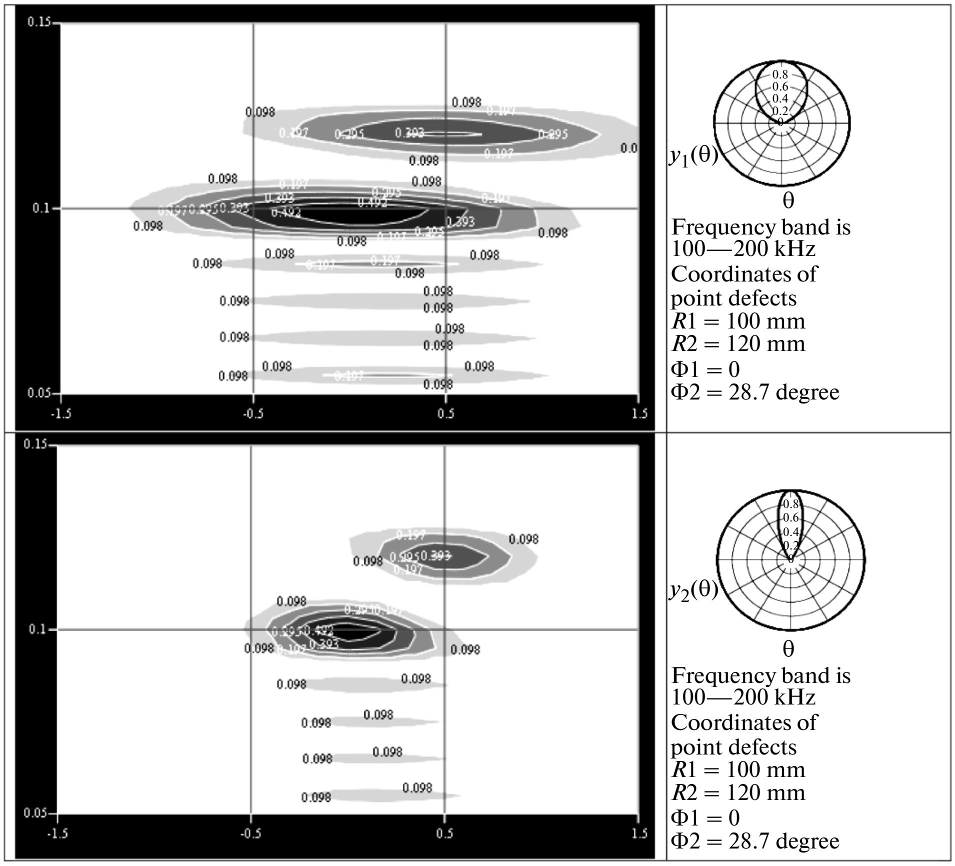

Fig. 4. Synthesizing the video pulse for diagnosing volumetric objects in an unrestricted domain with the parameter $V_{ph} = 10^3$ m/s, $\omega_1 = 100$ kHz, coordinates of point defects $R_1 = 100$ and $R_2 = 120$ mm. On the horizontal axis, the angle in radians and on the vertical axis, the distance in meters.

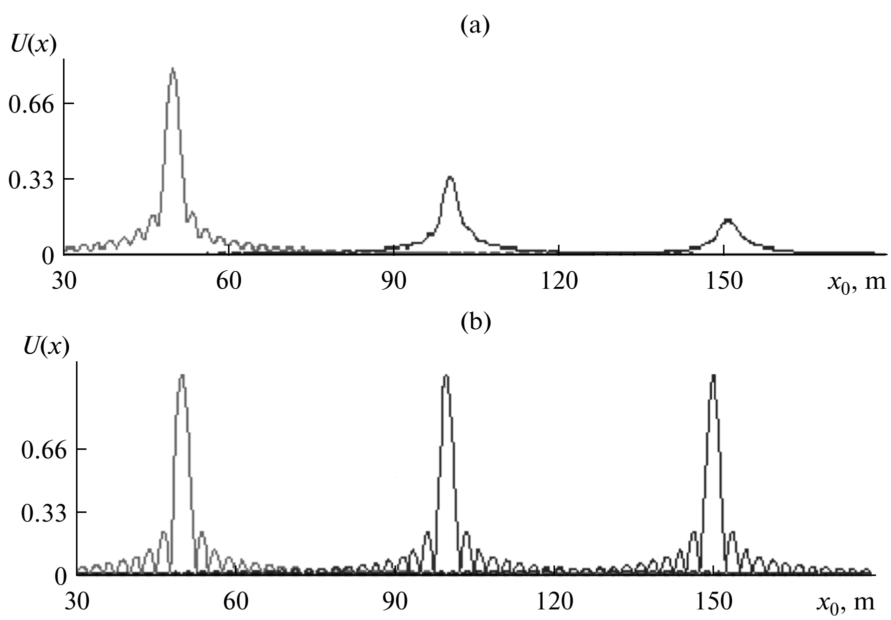

Fig. 5. Compensation of the influence of losses and dispersion: (a) without compensation; (b) with compensation. The parameters are as follows: the phase coefficient $\beta/k = 1.5$; the attenuation at the central frequency $\alpha = 0.0075$ 1/m; and the frequency band is 30–70 MHz, x_0, m.

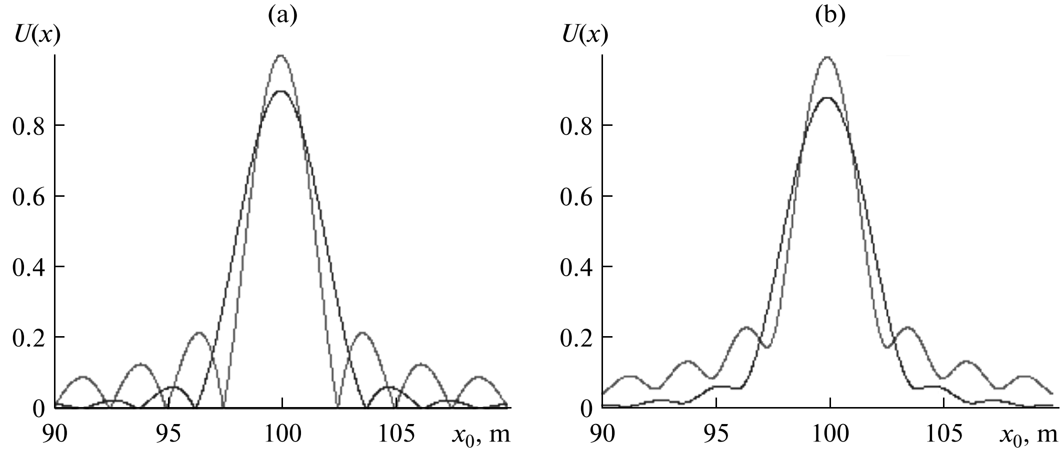

Fig. 6. The synthesized video-signal method for the constant and cosine weighting function: (on the left) in the absence of the attenuation and (on the right) in the presence of the attenuation at the central frequency $\alpha(f_0) = 0.05$ 1/m. The frequency band is 30–70 MHz. The distance on the horizontal axis is in meters.

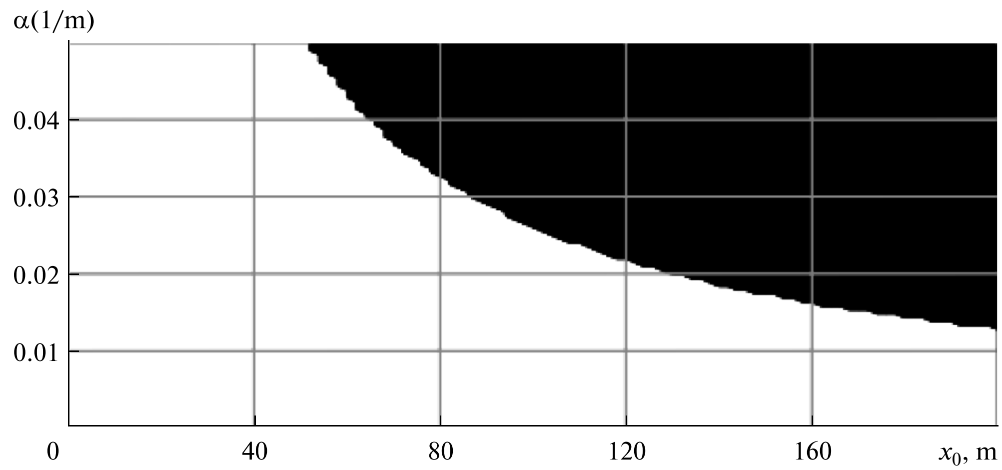

Fig. 7. The defect-detection region: on the horizontal axis, the range, m; on the vertical axis, the attenuation coefficient at the central frequency α (1/m). The frequency band is 30–70 MHz, the threshold attenuation level $U_{thr} = -40$ dB.

2.4. The Principle of the Compromise Selection of the Weighting Function. Adaptive Selection

As follows from the above, two evident boundaries exist for the selection of the weighting function. Its selection as $K_1(\omega) = \mathrm{const}\, e^{+\alpha(\omega)x}$ guarantees the constant *peak* width, and, hence, the constant resolution in the entire possible region of the range values $x_0 \le x_{0\max}$. The selection in the form of $K_2(\omega) = \mathrm{const}\, e^{-\alpha(\omega)x}$ ensures the maximum possible range. In this case, the *peak* width is at a maximum for the function $K_2(\omega)$ and at minimum for $K_1(\omega)$. The processing result with the uniform weighting function $K_3(\omega) = \mathrm{const}$ is a cross between $U_1(x)$ and $U_2(x)$ (Fig. 8).

The difference of the processing results in the line with a fixed attenuation coefficient is insignificant at small distances to the defect and greatly increases as it goes up. It is evident that the detection range and determination accuracy of the location of the irregularity are among the most important indices. Therefore, to reach the maximum efficiency, it is expedient to admit the possibility of changing the weighting function in a distance interval of $x \in [0, x_{\max}]$: $K(\omega) \to K(\omega, x)$.

The control over changes in $K(\omega, x)$ is based on the following considerations. While approaching to the maximum possible distance, the use of the weighting function $K_2(\omega, x)$ becomes the only possible one. In this case, the *peak* width cannot be farther decreased. As the irregularity approaches the beginning of the observed line, it becomes possible to use the weighting functions that ensure a higher resolution. This means that it makes sense to consider the compromise version, i.e., a weighting function in the form of

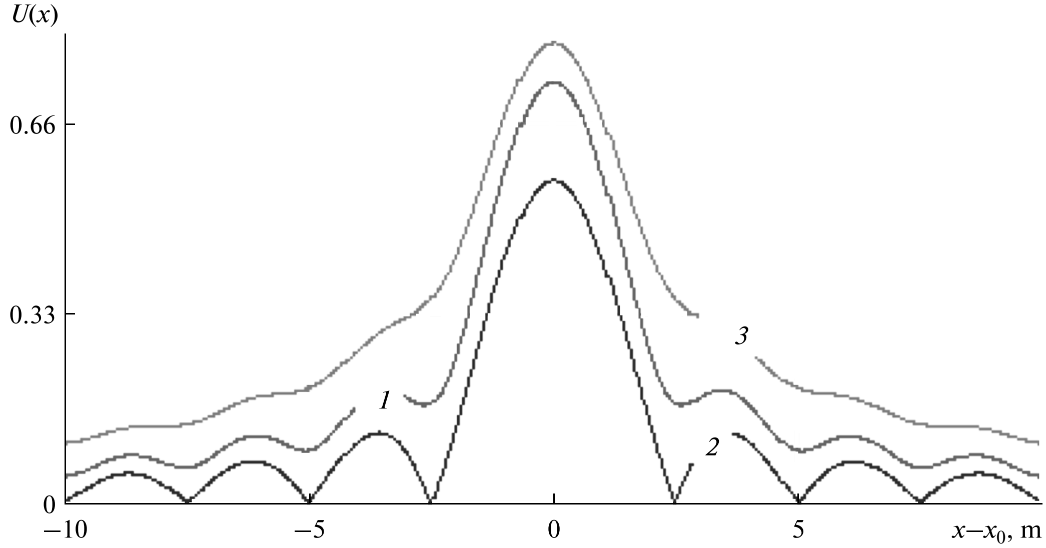

Fig. 8. Synthesized reflected signal for an irregularity located at a distance of 110 m in the UTR cat 5e twisted-pair cable with different weighting functions: (*1*) $K(\omega, x) = \text{const}$; (*2*) $K(\omega, x) = \exp[-2\alpha(\omega), x]$; (*3*) $K(\omega, x) = \exp[2\alpha(\omega, x]$.

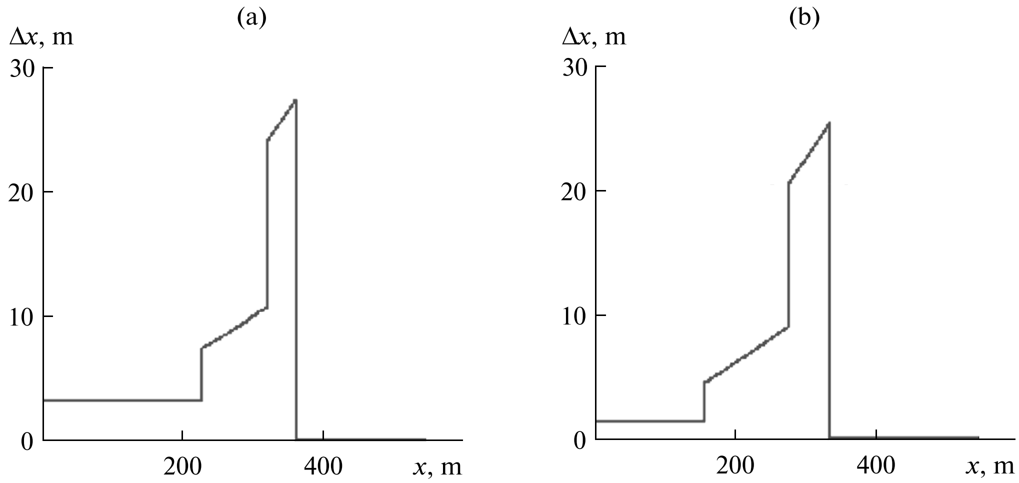

Fig. 9. The ultimate attainable resolution values for three gradations of parameter $y(x)$. The threshold attenuation level is −60 dB: (a) the frequency band is 10–50 MHz; and (b) 10–100 MHz. The cable is the UTR cat 5e twisted-pair cable.

$e^{+\alpha(\omega)y(x)}$, where $-1 \le y(x) \le +1$. In this case, it is possible to obtain both the maximum detection range of the irregularity and the maximum attainable resolution for the specified frequency band and attenuation in the transmission line. When it is assumed that the distances to the irregularity are small, the weighting function with $y(x) = 1$ is selected, since in this case the response width is at its minimum. With the increase in the distance to the defect, as the amplitude of the response approaches the threshold value that corresponds to the sensitivity of the receiver, the parameter $y(x)$ changes right up to the final value $y(x) = -1$. Figure 9 shows the dependences of the maximum resolution with the three gradations of the weighting function, which correspond to the values $y(x) = 1$, 0, and −1.

5. PRACTICAL IMPLEMENTATION OF THE VIDEO-SIGNAL SYNTHESIS METHOD

The advantages of the described diagnostic method include the combination of the multifunctionally and simplicity of the hardware implementation. Let us again stress that all the above-considered versions that improve technical indices are reached for the unchanged instrumental base only by using different

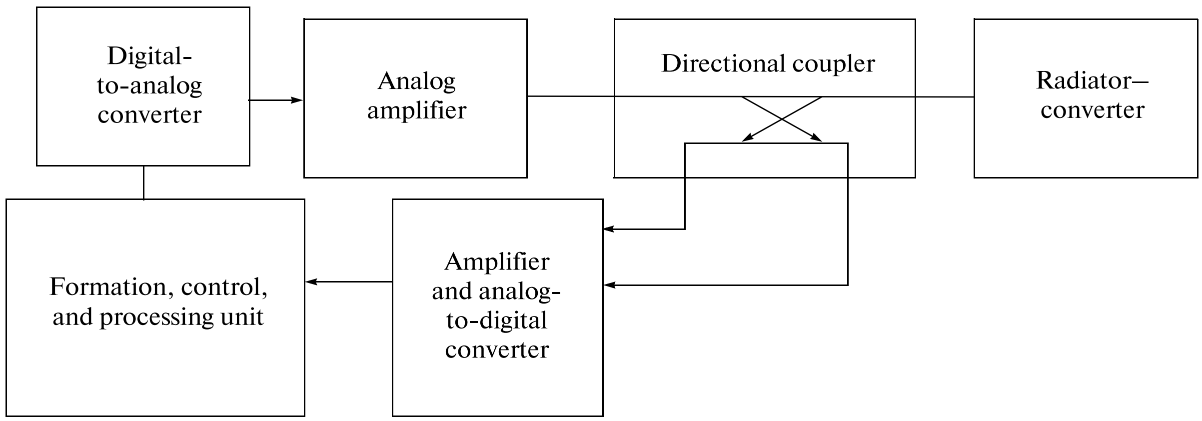

Fig. 10. A block diagram of the unit that performs the synthesized video-signal method.

versions of signal-processing algorithms, which correspond to the physical measurements of the reflection coefficient for probing oscillations at several different frequencies.

Depending on the frequency band that is used in the echo-location diagnostic equipment, several versions of the equipment are possible. In most cases, the upper frequency does not exceed several hundreds of MHz. For these cases, the principle of construction in which all of the basic operations are performed in the digital form is the most natural. Its simplified block diagram [16] is shown in Fig. 10.

The formation, control, and processing unit sequentially generates signals in the digital form at the frequencies f_i, $i = 1, ..., M$. After conversion into the analog form and corresponding amplification, the electric signals arrive at the converter input (acoustoelectric converter, antenna, and waveguide excitation unit) and excite waves in the studied volume. While the creation of excitation devices that convert the electric signal into the propagating electromagnetic or acoustic wave for a frequency band of about an octave requires effort, it is not an unsolved problem. Antennas with broadband properties are well studied [18] and the construction of broadband acoustoelectric converters can be based on the conception of mosaic antennas [19]. After corresponding reverse conversions, the reflected waves contain information on the amplitude and phase of the total received signal. These are detected, amplified, and, after conversion into the digital form, arrive at the processing device for producing synthesized video pulses in accordance with the above-described algorithms.

CONCLUSIONS

The proposed method for the construction of diagnostic equipment that is based on synthesizing the output response from separate harmonic components allows one to achieve high indices of the equipment that is used for echo-location diagnostics.

All of the processing versions are implemented in the above-described scheme without any complications of the equipment simply by changing the parameters of the weighting function, thus making it possible to create diagnostic units with a flexible structure, including with adaptation to the application conditions in particular problems.

REFERENCES

1. Klyuev, V.V., *Nerazrushayushchii kontrol' i diagnostika* (Nondestructive Testing and Diagnostics), Moscow: Mashinostroenie, 2003.
2. Ermolov, I.N. and Lange, Yu.V., *Nerazrushayushchii kontrol'. Spravochnik v 7 t. T. 3. Ul'trazvukovoi kontrol'* (Nondestructive Testing. Handbook in 7 Volumes. Vol. 3. Ultrasound Testing), Moscow: Mashinostroenie, 2004.
3. *Nerazrushayushchii kontrol'. Spravochnik v 8 t.* (Nondestructive Testing. Handbook in 8 Volumes), Klyuev, V.V. and Matveev, V.I., Eds., Radio Wave Testing, Second Edition, Moscow: Mashinostroenie, 2006.
4. Finkel'shtein, M.I., Karpukhin, V.I., Kutev, V.A., and Metelkin, V.N., *Poverkhnostnaya radiolokatsiya* (Surface Radiolocation), Moscow: Radio i svyaz', 1994.
5. *Voprosy perspektivnoi radiolokatsii* (Issues of Promising Radiolocation), Sokolov, A.V., Ed., Moscow: Radiotekhnika, 2003.

6. Tikhonov, V.I., *Optimal'nyi priem signalov* (Optimal Reception of Signals), Moscow: Radio i svyaz', 1983.
7. Smith Paul, Furse Synthia, and Gunther, Analysis of Spread Spectrum Time Domain Reflectometry for Wire Fault Location, *IEEE Sensors J.*, 2005, vol. 5, no. 6, pp. 1469–1478.
8. Lo Chet and Furse Cynthia, Noise-Domain Reflectometry for Locating Wiring Faults, *IEEE Transitions on Electromagnetic Capability*, 2005, vol. 47, no. 1, pp. 97–104.
9. Naik Suketu, Furse Cynthia, and Farhang-Boroujen Behrouz, Multicarrier Reflectometry, *IEEE Sensors J.,* 2006, vol. 6, no. 3, pp. 812–818.
10. Arkhangel'skii, V.B., Glagolev, S.F., Marchenko, K.V., and Semin, A.V., *Korrelyatsionnyi reflektometr so slozhnym zondiruyushchim signalom* (Correlation Reflectometer with Complex Probing Signal), Moscow: Foton-Ekspress, 2004.
11. Arkhangel'skii, V.B., Glagolev, S.F., and Marchenko, K.V., *Integriruyushchii reflektometr* (Integrating Reflectometer), Moscow: Foton–Ekspress, 2004.
12. Bylin, A.R., Bylina, M.S., and Glagolev, S.F., *Funktsional'nye vozmozhnosti impul'snykh reflektometrov* (Functional Possibilities of Pulse Reflectrometers), Moscow; Vestnik svyazi, 2007.
13. Bylina, M.S. and Glagolev, S.F., Increase in determination accuracy of distances from reflectgrams of cable circuits, *Kabel'-News*, 2011, no. 5.
14. Bylina, M.S., Glagolev, S.F., and Dyubov, A.S., *Novye vozmozhnosti impul'snogo metoda izmerenii parametrov kabelei dlya tsifrovykh sistem peredachi* (New Possibilities of the Pulse Measurement Method of Cable Parameters for Digital Transmission Systems), Moscow: Electrosvyaz', 2010, part 2.
15. Dyubov, A.S., Device for measuring quantitative and statistical characteristics of internal inhomogeneities of symmetrical high-frequency communication cables, *Polzunovsky vestnik*, 2010, no. 2.
16. Sedel'nikov, Yu.E. and Fadeev, L.Yu., RF Patent 2446407, 2012.
17. Sedel'nikov, Yu.E. and Fadeev, L.Yu., Method of synthesizing the video signal in defect diagnostic problems of transmission and communication lines, *Testing. Diagnostics*, 2013, no. 8, pp. 55–60.
18. Neganov, V.A., Tabakov, D.P., and Yarovoi, G.P., *Sovremennaya teoriya i prakticheskie primeneniya antenn* (State-of-the-Art Theory and Practical Applications of Antennas), Neganov V.A., Ed., Moscow: Radiotekhnika, 2009.
19. Kashin, A.V., Sedakov, A.Yu., and Shorokhova, E.A., Microwave antennas with an increased bandwidth, *Antennas,* 2010, vol. 7, no. 158, pp. 5–25.
20. Kartashev, V.T., Popko, V.P., Shalimova, E.V., and Konom, M.M., Designing of wideband mosaic antennas, http://library.mephi.ru/data/scientific-sessions/2002/Innovac_1/078.html

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