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ACOUSTIC METHODS

Ultrasonic Multichannel Flaw Detector for Testing Rails with Signal Recording

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Abstract—Although automated testing instruments have been introduced intensely on the railways of Russia, up to 95% of hazardous flaws in rails are detected by ultrasonic two-line (removable) flaw detectors. The paper describes the functional diagram and basic functions of an ultrasonic detector of the new generation, AVIKON-01, with continuous recording of data. The instrument is supplied with the software package for analysis of testing results, and it has advantages of both hand-held removable flaw detectors and high-performance instruments for nondestructive testing of rails.

INTRODUCTION

Presently two-line carriages for flaw detection are the basic instruments for testing rails laid on the Russian railway tracks. Although modernized instruments for rapid testing have been actively introduced in recent years with the aim to reduce the cost of operations, presently they still cannot fully replace the traditional mobile flaw detectors. In addition to the high accuracy and reliability of tests, the flaw-detector carriages have another advantage: in the process of testing, they do not disrupt the passage of trains because, when a train is approaching, the carriage can be easily removed from the track by two operators.

The Ministry of Railways of Russia has assigned the NDT operators the task to reduce the frequency of tests using various instruments, but, at the same time, to maintain the level of safety of rail tracks. The fulfillment of this task is helped by equipping flaw detector carriages with devices recording all data of continuous rail track tests [1]. The main advantage of the recording devices added to the two-line flaw detectors, which have traditionally yielded information about flaws in rails only in the audio and visual form, is that the features of such detectors are combined with the advantages of the rapid testing instruments, and testing data characterizing long sections of tracks are recorded.

The addition of recording devices to movable flaw detectors sets the diagnostics of rail tracks to the modern technical level, at the same time, the operational cost of rail track maintenance is reduced.

FUNCTIONAL CAPABILITIES OF THE FLAW DETECTOR

One of the instruments of the new generation is the AVIKON-01 ultrasonic flaw detector equipped with the RI-01 recorder (Fig. 1) developed by OAO Radioavionika. The potentialities of the multichannel mechanized flaw detector AVIKON-01 are determined, first of all, by the efficient scheme of sounding of tested objects (Fig. 2), the format of information displayed for the operator, servicing functions of the instrument, and the software supporting these functions.

In addition to the mirror-shadow and echo methods, the sounding scheme for rail flaw detectors includes the mirror method of testing [2] and two-beam sounding of bolted junctions [3]. Components of contemporary microprocessor circuits used in the instrument essentially improve its ergonomic parameters and allow the use of advanced algorithms of signal processing.

The convenient mnemonic format of displayed information (Fig. 3), in addition to the traditional audio indication, enables the operator to determine rapidly the number of a channel where the echo-signal amplitude is above the preset threshold level.

An important feature of the recording apparatus in the instrument discussed is the multilevel detection. Traditional records of testing signals and their conversion to the one-threshold B-scans,

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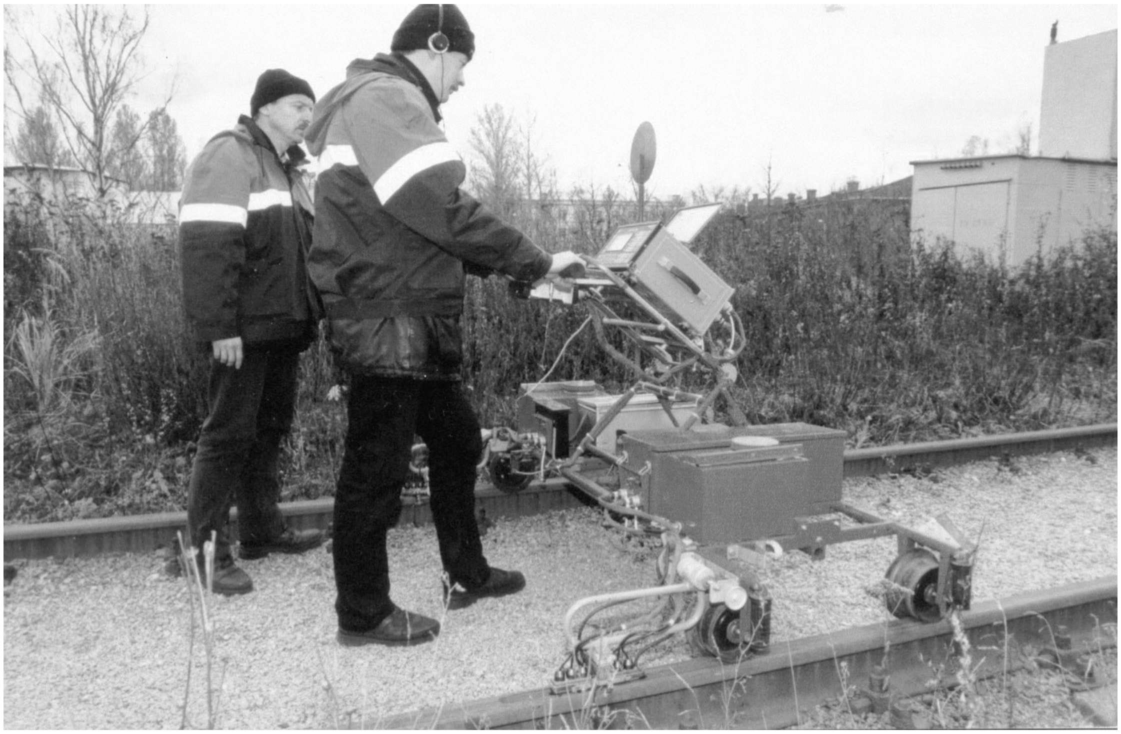

Fig. 1. AVIKON-01 flaw detector equipped with RI-01 data recorder.

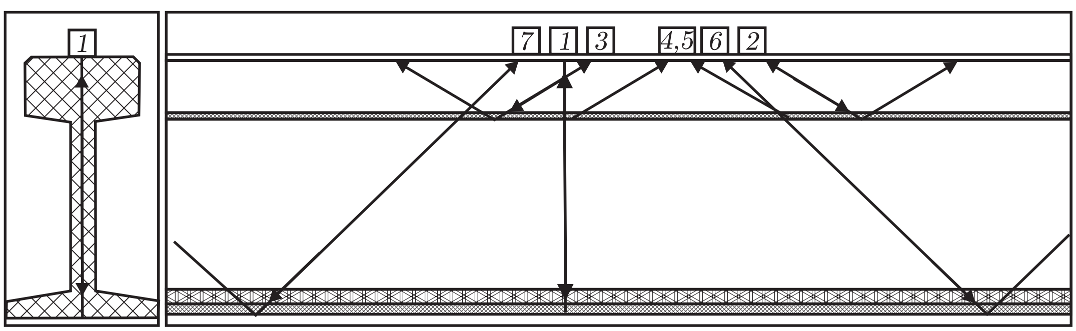

Fig. 2. Diagram of sounding and configuration of detecting system for AVIKON-01 portable flaw detector: (*1*) direct-input piezoelectric transducer generating ultrasonic waves for mirror-shadow and echo-testing of rail webs and flanges; (*2*) and (*3*) angle transducers generating ultrasonic waves for testing rail heads; (*4*) and (*5*) angle transducers generating ultrasonic waves for mirror testing (in combination with transducers *2* and *3*) of rail heads (both are mounted in the same casing); (*6*) and (*7*) angle transducers for echo testing of rail webs and flanges.

which are widely used in instruments for rapid testing, do not contain information about amplitudes of received echo-signals. Therefore, detailed analysis of flawed sections cannot determine such an important characteristic as the coefficient of flaw detectability K_{d}. Moreover, some methods of nondestructive testing require measurements of bottom-reflected and echo signals. Therefore, the system of multilevel recording essentially upgrades the instrument. In addition, introduction of several detection thresholds corresponding to higher levels of susceptibility than that in the system of automatic flaw indication (AFI) enables the operator to analyze flaws on early stages of their development.

The recorded parameters of echo signals are the delay with respect to the sounding pulse and the amplitude estimated using eight threshold levels preset in the instrument. One of the most

Fig. 3. Mnemonic display of testing data.

important characteristics of a flaw detector is the error in the echo-signal delay with respect to the emission of the sounding pulse. In practical inspection of rails, errors in coordinates and effective dimensions of flaws are usually within ±1 mm. As follows from the known expressions for flaw coordinates, this accuracy can be achieved when the arrival time of echo signals is measured with an uncertainty no higher than 0.33 μs for transverse waves (right transducers), and 1.0 μs for longitudinal waves (angle transducers). In order to relate the detected pulses to the distance passed, the position transducer measures the distance with a quantization step of 3 mm, which is sufficient for practical tests of rails.

The essential parameter of testing systems with parallel recording of all signals is the minimal number of manipulations in the process of recording. Therefore, before starting a test, the operator should enter only information about the time of test and position of the tested section of the track. After entering the initial data, the operator switches the instrument to the basic mode of continuous testing of rails. Further, the manipulations with the instrument during the continuous testing include only pressing the buttons “Kilometer correction” and “Special marks” in passing each kilometer post and picket posts. As a result, the screen displays numbers of kilometer and picket posts, which can be corrected, if necessary, using the buttons on the instrument’s panel. To obtain more accurate reference points on the track, the operator can use the button “Special” and thereby mark characteristic objects on the track. These marks may correspond to bridges, level crossings, platforms of suburban stations, rail storages on each kilometer, etc.

The indisputable advantage of the rail testing by two-line flaw detectors is the possibility of making an ultimate decision on the quality of the tested track taking into account not only the data of continuous testing, but also visual and tactile information obtained by the operator during inspection of a flawed section. A skilled operator in this case compares the recorded data with measurements of the neighboring flawless portion of the track. Moreover, he can also test the suspicious section of the rail using a manual piezoelectric transducer applied to any surface of the rail (to the side surfaces of the rail head, web, and flange). For example, the program for the AVIKON-01 instrument includes six modes of operation with various hand-held transducers (with entrance angles of 0, 45, 50, 58, and 65° and operating in the echo and echo-mirror modes). Measurements by the hand-held instrument can also be recorded in the memory. After selecting the required parameters, the operator presses the button initiating the signal recording. In this case, the screen displays the remaining time of scanning in seconds.

After the end of testing of a track segment, the operator terminates the séance by pressing two buttons. As the memory, which is sufficient for testing segments up to 140 km, is filled, the data should be transmitted to a computer. If the memory is overflown on the track, the instrument displays a warning and automatically closes the current file of testing data.

PROGRAM FOR DISPLAYING AND ANALYSIS OF TESTING DATA

For the subsequent analysis and compilation of reports, all records from tested segments are stored with the help of a dedicated software package in a computer data base. The settings of the displaying program include serial numbers of the flaw detector and recorder, the name of the railroad, and the list of operators working with this instrument and the programs, which will facilitate compilation of the list of tests. The data base for testing data is formed when the data are transferred from the recorder memory to the computer. In this process, files with testing data are written in folders of the data base with names indicating the tested segments of tracks. The file name is generated automatically when the data are read from the recorder memory. The file name includes the date of testing and the number of the kilometer where the test started. For example, if the data base is written on disk C: in the directory with name BASE, the full name of the file containing results of testing on the segment between stations Pushkin and Pavlovsk conducted on June 24, 2002 and indicating its position is presented as follows:

C:\BASE\Pushkin–Pavlovsk\240602_25_7.dat,

where 240602 denotes the date of testing, 25 is the initial coordinate of the tested segment in kilometers, and 7 is the file number for this track segment.

Signals of continuous ultrasonic tests of rails are traditionally displayed in the form of bright spots on the plane with coordinates plotting the travel time of ultrasound in a rail and the distance through which a transducer (NDT carriage) has passed. Such pictures displaying signals are dubbed B-scans (where B means brightness) and extensively used in records of ultrasonic signals detected by ultrasonic motor-rail cars and flaw-detector cars [4].

In multichannel testing systems, which include all instruments for continuous testing of rails, B-scans show signals from each detector channel on separate tracks. Signals from similar channels, e.g., from the forward- (zooming-in) and backward-looking (zooming-out) angle transducers coupled to a rail head, are usually displayed on the same track. Thus, the testing procedure produces a multitrack pattern, which is not convenient for visual perception.

Since the task of looking up and analyzing signals recorded by carriage flaw detectors is largely commissioned to workers of NDT departments without extensive experience in interpreting traditional B-scans, signals may be presented in more convenient forms. It is the first time in the practice of rail inspection in Russia that an operator can display recorded signals in three different forms (Fig. 4):

(1) As traditional B-scans, which is convenient for analyzing signals in separate channels and habitual for operators of flaw-detector cars (Fig. 4a).

(2) In the form of B-scans, but with echo signals from different transducers translated to one cross section, which is convenient for analyzing signals received simultaneously by several detector channels (Fig. 4b). Such patterns are generated by a computer program, which transforms coordinates of reflectors with due account of entrance angles of ultrasonic beams from different angle transducers and their positions in the testing system.

(3) In the form of echo signals against the top view of the tested rail translated to the cross sections of their sources, which graphically shows positions of reflectors in the rail and enables operators without a lot of skill in interpreting traditional B-scans to rapidly identify the signal sources (Fig. 4c). In such patterns, the operator sees marks at the sites on the upper view of the rail where the reflectors are located (flaws, bolt holes, etc.).

It is noteworthy that the suggested forms of signal presentation were selected after serious discussions with workers of industrial research institutes and producers of flaw detectors, and these patterns were commissioned by the Ministry of Railways of Russia as the basic forms of graphs depicting signals detected in continuous inspections of rails.

The flaw diagrams reflect all signals due to bolt connections, surface and internal flaws. Packages of signals due to hazardous flaws are usually seen as clusters of tilted or horizontal dashes, and a

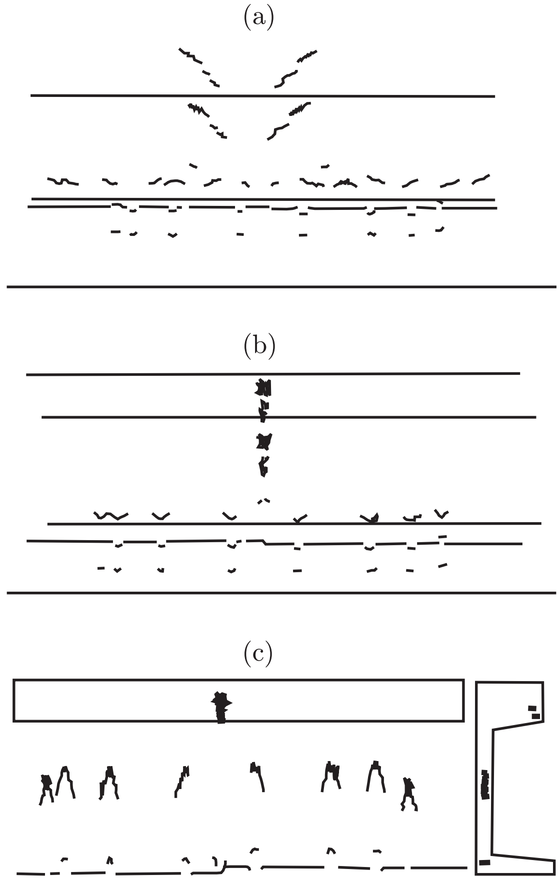

Fig. 4. Recommended forms of data displays used in interpreting flaw diagrams: (a) traditional form of B-scan; (b) modified B-scan; (c) locations of signal sources on the rail diagram.

skilled operator can determine the degree of hazard caused by a detected flaw using the shapes of such clusters. For a detailed analysis of signals, the graphic program allows the operator to display a pattern on an any desired scale. The screen can show signals detected on tested segments with lengths of 1 m to 10 km and with clear marks corresponding to kilometer posts and pickets (after each 100 m), as well as other "special" marks entered by the operator in the process of inspection. All these marks provide good references for flaws on real tracks. Moreover, the operator can display on the screen only signals recorded either from only one detector channel or from all detector channels used in inspection of both lines of a rail track (in the AVIKON-01 instrument two lines are tested using 20 channels).

In analyzing signals recorded in both continuous and manual tests, the operator can determine effective dimensions and depth of a detected flaw using a pattern displayed by the personal computer, which, undoubtedly, yield in most cases more accurate data then measurements of these parameters on track with the help of a scale rule.

The quality of an ultrasonic test can be judged by the continuous line of the bottom-reflected signal (the echo signal reflected from the bottom of the rail flange), sizes of trains of pulses reflected from elements of bolted junctions, and digital data on the sensitivity set up in each detector channel.

In practical testing, it is not a rare occasion that the operator has to correct the sensitivity in separate detector channels to the side of lower values as compared to those prescribed by the regulatory documents. The cause is the presence of rails with higher levels of structural noise on some segments of tracks and microcracks on tread surfaces, which do not reduce strength characteristics of rails, but generate echo-signals that turn on the audio indicator of the instrument. The feature of the instrument and data processing package which allows one to view the recorded signal at two levels of recording is equivalent to performing a record of one track segment at two levels of sensitivity simultaneously:

• at the level prescribed by the regulations;

• at the level a factor of two higher (6 dB) than that prescribed by the regulations.

This allows one not only to judge whether a change in the sensitivity of a detector channel introduced by the operator was justified, but provides a basis for analysis of flaw development using periodic tests of rail tracks. Since the main testing parameter for each detector channel are recorded, the testing data are reproducible, which is very important for monitoring the condition of a rail track. The basic principles of the rail condition monitoring with the help of the two-level recording of signals have been developed by OAO Radioavionika and patented [5, 6].

In the process of analysis (interpretation) of signals recorded on tested tracks, the data processing program allows the operator to save fragments of records in a separate data base designated for flawed and highly flawed rails, and to write information in an electronic notebook and a checklist. This permits one to generate and print a checklist on flawed track segments supplemented with fragments of flaw patterns and all relevant data (coordinates, relative sensitivity levels for each detector channel, the operator's name, the date of the review of flaw patterns, etc.), and after interpretation of all data in the file to generate and print the ultimate checklist.

Thus, the recording of signals detected in continuous tests of rail tracks by two-line flaw detectors solves the following problems [1]:

(1) objective information about the quality of tested tracks is recorded;

(2) parameters and regimes of tested conducted on tracks are recorded;

(3) the recorded information is saved for comparison with results of subsequent tests performed using removable and rapid flaw-detecting instruments;

(4) objective information concerning conditions of rail tracks is periodically recorded in certificates;

(5) quality of tests performed by operators of removable flaw detectors installed on carriages is monitored.

As follows from the analysis of recorded flaw patterns, continuous recording of signals on rail tracks by removable flaw detectors not only yields reliable information about rail conditions, but also enables one to check whether the technical rules of rail track testing and maintenance are complied with.

The recorded flaw patterns contain the information

• that a rail track has been tested by an operator;

• that the operator complied with the technical rules of testing for bolted junctions and rolled the carriage two or three times over each junction;

• about actual sensitivity levels for all detector channels;

• on rail track segments where acoustic contact was lost for one reason or another, i.e., the testing data are unreliable;

• on signals due to structural reflectors and flaws in tests of track segments with complex configurations, such as switch locations;

• on parameters of detected flaws (type, depth, and effective dimensions of flaws);

• on additional tests of specific rail cross sections performed using hand-held transducers;

• whether changes in sensitivity parameters in detector channels introduced by the operator on some track segments were justified;

• on cases when positioning of the tracking systems of the detector was disrupted;

• on coordinates of sites where the carriage was removed from the track to give way to a train;

• on actual conditions of the rail metal (high intensity of structural reflections, microcracks on the tread surface, and surface flaws on some rails and track segments).

The analysis of signals obtained in multiple passages of the detector carriage over specific track segments allows one not only to detect hazardous flaws with higher probabilities, but in some cases to follow the growth of flaws on their early stages of development by monitoring conditions of rails (Fig. 5). In future this will make it possible to repair rail tracks in accordance with a schedule by replacing flawed rails when cracks grow to critical sizes.

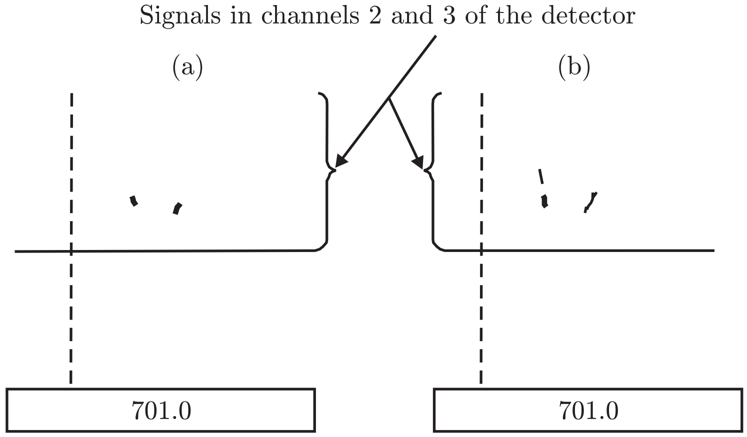

Fig. 5. Diagram of a flaw coded as 21.2: (a) in the first detector passage; (b) in the repeated detector passage (the effective flaw size has increased, which indicates that it is growing).

FUNCTIONAL DIAGRAM OF MULTICHANNEL FLAW DETECTOR WITH CONTINUOUS RECORDING OF SIGNALS

The structure of the AVIKON-01 multichannel flaw detector (Fig. 6) is based on the general principles of designing of ultrasonic detectors modified in accordance with requirements to modern instruments for ultrasonic testing.

Probing ultrasonic pulses are generated and echo signals are amplified and detected by an emitter-receiver unit (ER). This unit is driven by the data processor (DP), controls the concurrent operation of the left-hand and right-hand lines of the flaw detector and sequential operation of the channels in each line. The acoustic units of the left-hand and right-hand lines (AULL and AURL) each incorporate six piezoelectric transducers operating in accordance with the sounding scheme (see Fig. 2). The DP unit records in a permanent storage settings of each channel and digital parameters of their controls during tests. The information input/output subsystem (II/OS) of the DP unit polls the elements of the push-button panel (PBP) and displays information on a liquid-crystal screen (LCS).

The unit for data recording (DR) stores the entirety of detected echo signals, alongside current setting parameters of the flaw detector. In order to obtain all servicing information and control codes, the DR unit communicates with the central-processor unit (CPU) of the data processor.

The functional units of the recorder are driven by a recording controller (RC) and perform the following functions:

• receive and convert to the digital form video-signals from the ER unit for each rail line (VSLL and VSRL);

• distribute signals among 14 channels of continuous testing and 5 channels of manual testing (in accordance with the timing chart for the ER unit;

• averages echo signals over one step of the distance transducer;

• detects bottom reflections for each rail line and eight maximal pulses within one time window;

• records in the programmable read-only memory (PROM) detected echo-signals and setting data in a preset format.

The recorder processes the data sequentially in three stages:

• video-signals are digitized in accordance with the preset voltage thresholds in the ADC and averaged over one quantization step of the distance transducer (I);

• eight maximal pulses are selected within one time window for each channel by the maximum search unit (MSU);

• records are formed by the record forming unit (RFU) in the preset format using the MSU output.

This configuration allowed us to integrate MSU and RFU for the left- and right-hand rail lines, thereby the cost of the hardware was reduced.

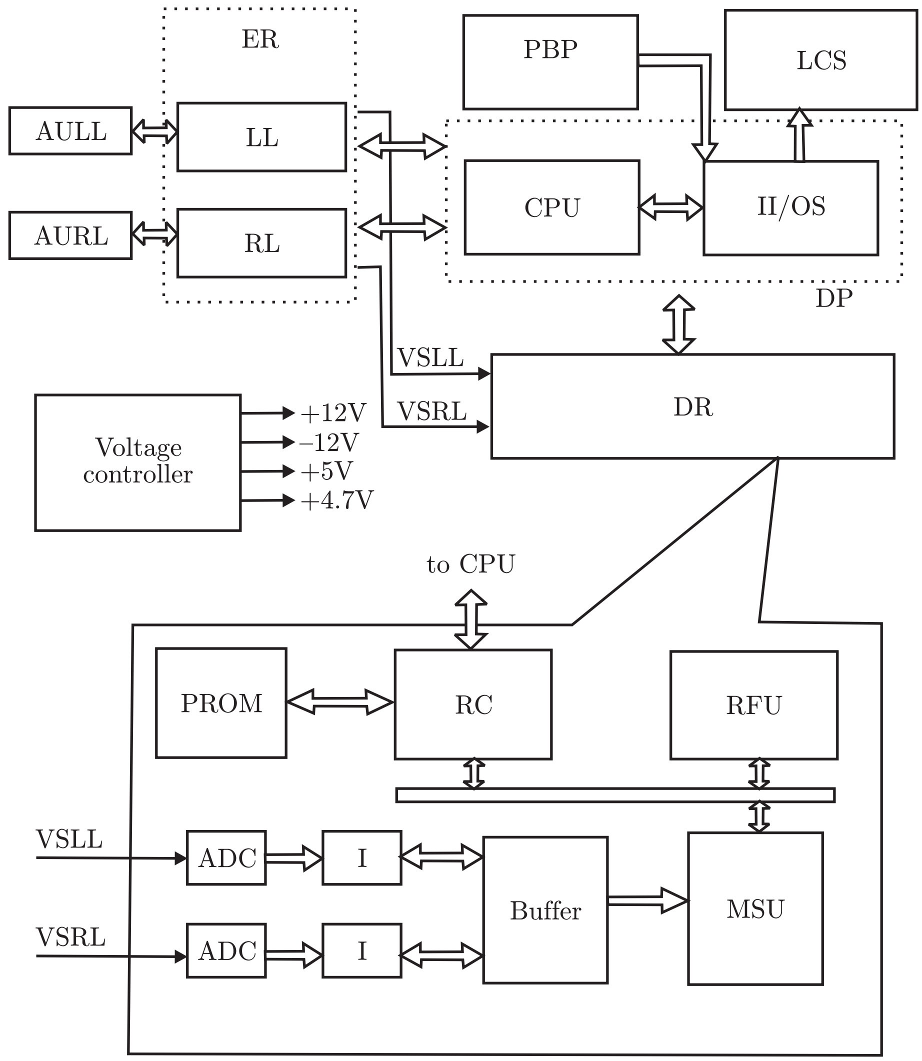

Fig. 6. Block diagram of the AVIKON-01 flaw detector.

In order to limit the amount of processed data without a loss of information, which is very important when the capacity of the recording medium is limited, some simplifications were introduced to the processes of recording and retrieving signals obtained in the process of testing.

As was noted previously, the data recorder RI-01 implements an algorithm searching for eight pulses of the highest amplitudes within the time window for each channel. As follows from the results of operational tests, these data are sufficient for reconstructing A-scans for each testing cycle.

Figure 7a illustrates selection of signals for recording. For example, echo-pulses *2*, *7*, and *11* should not be recorded because they are not among the eight pulses of the highest amplitudes, although they belong to the time window. After the digital processing of the video-signals from the receiving transducer, the maximal ADC threshold surpassed by the detected pulse and the delay of the threshold crossing with respect to the probing pulse are recorded (Fig. 7b).

In order to record signals of the mirror-shadow method (such signals are present in almost every testing cycle), the recorder operates to a dedicated algorithm and stores only changes in the bottom-reflected signal with respect to the latest record. This also enabled us to reduce the memory volume needed for signals that are present in almost every testing cycle.

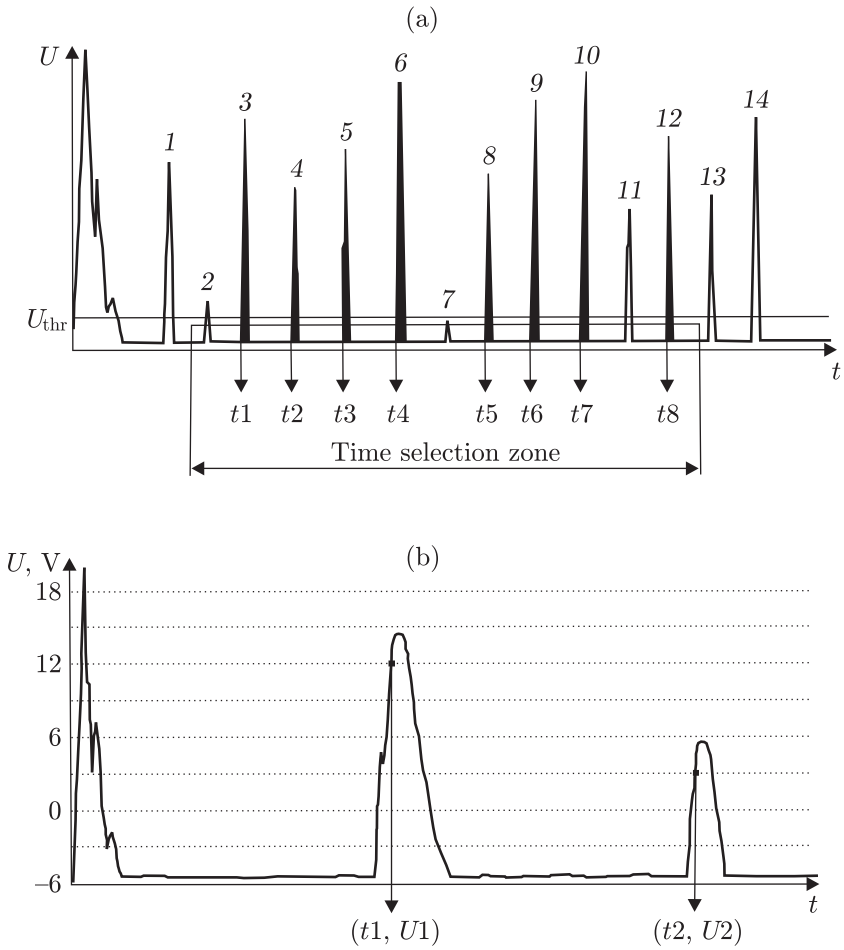

Fig. 7. Diagrams illustrating algorithm of data selection in the flow of echo signals: (a) selection of highest eight pulses; (b) determination of pulse parameters.

RESULTS OF OPERATIONAL TESTS OF THE AVIKON-01 FLAW DETECTOR WITH THE DATA RECORDER

In order to finish the techniques used in the new flaw detector, we conducted operational tests of the instrument starting at the end of the year 2001. Two AVIKON-01 detectors equipped with RI-01 recorders were operated on two lines of Oktyabr'skaya rail road. In the first months of 2002 alone, testing signals were recorded over a distance of about 600 km. As was expected, the quality of recorded signals was better than the quality of records obtained by flaw-detecting motor-rail cars and rail cars coupled to trains owing to the more stable acoustic coupling of the AVIKON-01 transducers.

Basing on the operational tests of the AVIKON-01 instruments equipped with the data recorders RI-01, the data base of flawed and highly flawed rails is being compiled. In this data base, the flaws are classified in accordance with the NTD/TsP-1/93 regulation [7]. This classification allows one to monitor the dynamics of accumulation of flaws of specific groups. Moreover, it becomes possible to monitor development of some flaws by comparing records of one segment of the track made at different times.

Thus, the flaw detectors equipped with data recorders improve the accuracy and reliability of ultrasonic tests of railways. The advantages of the new technique are both in the higher discipline of operators working with the new instruments and due to additional information recorded in such tests.

CONCLUSIONS

With the help of the algorithm selecting signals for records, which are used in the multichannel ultrasonic AVIKON-01 detector of the new generation, we have achieved the required quantity of information in the recorded data. The implemented configuration of ultrasonic sounding and the sequence of transducer operation enabled us to reduce the cross-talk between channels, with due account of the shape of tested objects. Using the minimal additional hardware, we managed to measure and record parameters of echo-signals in each of the 20 data channels with the required errors and quantization steps at the maximal rate obtainable with such testing devices. The suggested schemes of data recording and processing show promise in view of creating an efficient system for predicting conditions of rail tracks and optimizing the frequency of ultrasonic tests. The rapid decoding and analysis of recorded data by skilled engineers may reduce the probability of erroneous conclusions made by NDT operators concerning the degree of hazard due to flaws in tested rail tracks.

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