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Magnetic Flux Leakage Method of Railway Rails Defects diagnostics and its Place Among Mobile Means of Non-destructive Testing

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Summary
The task of mobile railway tracks defects diagnostics is to identify and recognize dangerous defects in order to prevent possible accidents. A review of the methods for controlling the physical and mechanical characteristics of metal constructions of engineering objects of long-term exploitation, which are used under different temperature regimes and conditions, is carried out in Among the described non-destructive methods on the used physical fields are allocated: magnetic, acoustic, electromagnetic, thermal and electrical. Electromagnetic methods are successfully used in various industries, such as the railway industry, the metal-working industry, the drilling, nuclear waste storage and so on. In particular, in the railway industry, using the technique of measuring the electromagnetic field of an alternating current, checks of carriages, wheel pairs and tracks are carried out. Recently, hybrid systems of diagnostics on the basis of carriages-defectoscopes are actively used to detect defects in railway tracks while simultaneously using magnetic, ultrasonic, visual-measuring and optical methods of non-destructive control. The high efficiency of new methods for constructing the information diagnostic system (IDS) of mobile magnetic railway tracks defectoscopy objectively depends on the successful solution of the certain contradiction: this is the provision of high resolution and sensitivity of IDS for the detection, differentiation and classification of the defects signals – on the one hand, and on the other hand – reduction of the time allocated for the defectoscopic examination in the conditions of various obstacles and the need for defects detection in the early stages of their development. Solving this contradiction with the use of modern methods of railway tracks defects signals processing and new small size multichannel and component sensors forms the content of an important application problem, which is considered in this article.

Keywords: information diagnostic system, railway tracks defectoscopy, component sensors, non-destructive magnetic methods, wavelet analysis and neural networks

1. Introduction

Today, rail networks around the world are becoming increasingly loaded with trains travelling at higher speeds with a large number of passengers and heavy freight wagons, which create more traffic loads on railway tracks than before. All this leading to increased demand for control and maintenance of railway tracks. The expenditure for inspection and maintenance of railway tracks has steadily increased over the last few years, which is accompanied by a significant improvement in quality indicators in this area:

- the improvement in the safety of the railway system;
- the development of new rail networks to accommodate the continued growth in demand;
- contributing to a more stability of rail networks, in both environmental and financial terms, by delivering further efficiencies and exploiting technological innovation.

Thus, maximum reliability of the railway network can be achieved only after sufficient and reliable inspection and maintenance of rail network. Early defectoscopy of rails performs the primary role in the

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detection and identification of dangerous cracks on the rails from rolling contact fatigue (RCF) in order to prevent possible accidents and, therefore, is of paramount importance for the safe and reliable exploitation of rail networks around the world.

Despite this, the railway equipment for non-destructive mobile diagnostics of defects for long time did not received sufficient funding. It became more accessible only after a series of serious accidents (for example in the Hatfield-city (Hertfordshire County, East England, October 2000)). Appropriate use of limited funding in this case is very important.

A review of the methods for controlling the physical and mechanical characteristics of metal constructions of engineering objects of long-term exploitation, which are used under different temperature regimes and conditions, is carried out in [11, 12].

Among non-destructive magnetic control methods, which have long been used in the mobile diagnostics of railway tracks defects, the most common are Magnetic Flux Leakage Method and Alternative Current Field Measurement Method. Magnetic methods of defectoscopy are well diagnosing top of the rail, actually rail head.

Ultrasonic methods occupy an important place in railway tracks defectoscopy [16–18]. Ultrasonic diagnostic methods, despite the difficulty of providing reliable acoustic contact with the surface of the rail, the need for large quantity of contact liquid and the limiting diagnostic speed, can diagnose web and foot of the rail. The advantage of ultrasonic methods is also possibility to estimate sizes and position of the defect, which ultimately provided the intensive development of research in this area [5, 11].

On figure 1 the principle of measuring the transverse, longitudinal and angular cracks of the head of the rail is shown using a set of three ultrasonic sensors placed at different angles relative to the surface of the rail. Also, this figure shows the cross-section of the rail along with a set of sensors located on it.

Electromagnetic methods are successfully used in various industries, such as the railway industry, the metal-working industry, the drilling, nuclear waste storage and so on [26]. In particular, in the railway industry, using the technique of measuring the electromagnetic field of an alternating current, checks of carriages, wheel pairs and tracks are carried out.

Recently, hybrid systems of diagnostics on the basis of carriages-defectoscopes are actively used while simultaneously using to detect defects in railway tracks magnetic, ultrasonic, visual-measuring and optical methods of non-destructive control [11].

The high efficiency of new methods for constructing IDS of mobile magnetic railway tracks defectoscopy objectively depends on the successful solution of the certain contradiction: this is the provision of high resolution and sensitivity of IDS for the detection, differentiation and classification of the defects signals – on the one hand, and on the other hand – reduction of the time allocated for the defectoscopic examination and increasing the accuracy of the diagnosis in the conditions of various obstacles and signals from the sleepers substrates and the need for defects detection in the early stages of their development. Solving this contradiction with the use of modern methods of railway tracks defects non-stationary signals processing by applying wavelet transforms and neural networks and building a diagnostic system based on new small size multichannel and component sensors forms the content of an important application problem.

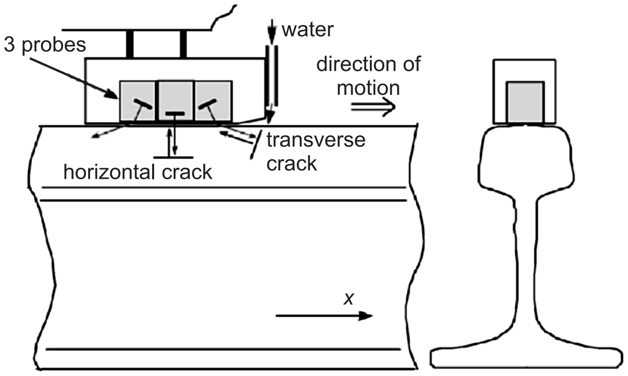

Fig. 1. Measurement of defects in railway track by ultrasonic method [11]

2. Ultrasonic methods of mobile diagnostics of railway tracks defects

Ultrasonic test equipment is widely used in the railway industry to check for any internal defects and control the rails in operating mode.

In most cases the test of the rails made with the help of special ultrasonic sensors installed on the test train undercarriage. For connection of piezoelectric transducers and rails sliding sledge-plates or liquid filled wheel ultrasonic sensors are used. Standard ultrasonic sensors have a poor ability to detect when defects are surface or near-surface. For this reason, using a set of sensors placed at different angles in order to ensure detection of surface and near-surface defects (Fig. 2).

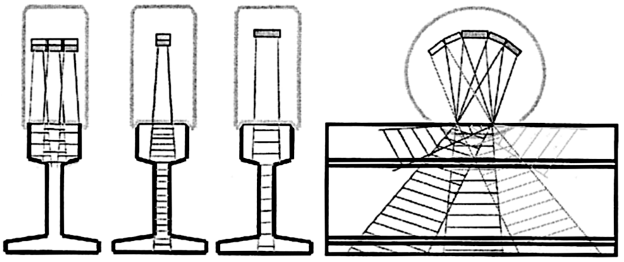

Fig. 2. Increasing the ability to detect defects by using a set of sensors [11]

During the inspection of rails using conventional ultrasonic sensors a beam of ultrasonic energy in the form of oscillation is transmitted to the body of the rail. The reflected ultrasonic oscillation energy is then detected using a set of transducers. The amplitude of any reflected impulses during the diagnostics contains valuable information about the integrity of the rail and its defects. Since the defects are unpredictable, the spread of ultrasonic oscillation in the rail occurs at different incident angles in order to maximise the Probability of Detection of any dangerous defects present in the rail. The refracted angles generally used are 0°, 37° or 45° i 70°.

In many countries, this method is typically employed on Sperry diagnostic trains (models «UTU1», «UTU2» and «UTU5» – from eng. Ultrasonic rail Testing Unit (UTU)). The presence of detected defects by the train of UTU type is confirmed by the deployment of portable ultrasonic inspection units known as Sperry Stick. On Figure 3, a shows such a typical portable ultrasonic rail inspection unit, guided by the operator [11].

Diagnostic trains Eurailscout (Netherlands, Germany, etc.) and Scanmaster (Israel) use sliding plate sleds to accommodate the ultrasonic sensors system, as shown in Figure 3, b. These trains operate at a speed of 72 km/h, but the potentially possible inspection speed is up to 100 km/h [11].

One of the problems faced by such trains UTU1 – too many "false" readings, which increases the cost of staff time, since any such operation should be studied in detail. This problem is partly solved by increasing the operation threshold and comparison of diagnostic train results with portable systems results to refine the detection criteria.

UTU2 probe contains a large array of sensors, providing better and more complete ultrasonic irradiation of rail. The probe array, consisting of 9 separate sensors, is contained within a liquid filled tyre, known as a Roller Search Unit (RSU). UTU2 has two such units to provide testing continue if one RSU can not function correctly or fails.

Portable ultrasonic inspection device Sperry Stick is a hand operated version of the RSU and is used as a means to check the data of both types of ultrasonic trains. The comparison of results from unit UTU2 with those from the Sperry Stick shows coincidence of defects identification results by 90-95%.

Development and improvement of these systems in order to reduce the time allocated for defectoscopic examination by increasing scanning speeds are involved United States and United Kingdom (Network Rail Company). UTU2 can operate at speeds up to 65 km/h, however, to ensure high accuracy sensors must irradiate defect by the ultrasonic 4 times and so in practice they operate at a speed of 45 km/h. UTU5 diagnostic trains using enables 40% faster, more efficiently and reliably rails defects and their bolt connections detection (including their cracking). This ensures by the high compliance of RSU tyre form to the rail surface form, even with the high wearing and deformation of the latter.

The equipment on trains such UTU not determine the size of all existing defects and their exact location. This equipment can only reliably detect defects in the form of deep cracks in the range of 15–25° angles from vertical in any direction. Cracks smaller than 5 mm in depth and cracks under other angles are difficult to detect. This is the main problems and limitations faced by trains UTU type:

- very cold weather, the formation of the intermediate layer due to rail icing;
- spilled oil, which also leads to the intermediate layer occurrence that can affect on test results even up to 100 m from the RSU;

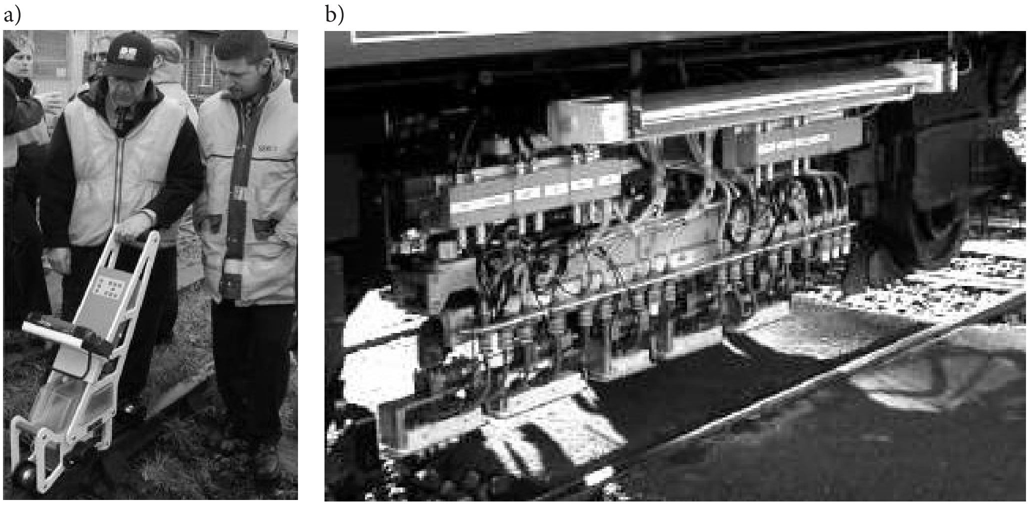

Fig. 3. Ultrasonic defectoscopy technique [11]

- destruction of RSU tyre by the damage rail, which occurs on average once a week;
- complexity of identification of vertical/transverse defects;
- low speed of procedure of defects diagnostic using portable RSU defectoscope (2–3 km/h).

3. Magnetic methods of mobile diagnostics of railway tracks defects

Magnetic methods in rails defectoscopy have a long history. The origin of the magnetic method of rails control can be considered the end of the 20's – the beginning of the 30's years of the last century. At that time (in 1928), in Japan, M. Suzuki offered the first magnetic defectoscope, which was a self-propelled railcar equipped with magnetization system in the form of a P-shaped direct current electromagnet (on each thread of the track) and the induction sensors placed between the poles of an electromagnet and a device for recording test results on paper tape. This defectoscope allowed detecting internal rail head defects and cracks with access to the rail surface at the speed of the defectoscope up to 4 km/h.

Also in 1928 on the order of firm "ARA" (American Railway Association), Elmer Sperry developed defectoscope for transverse cracks detection in the rail head (Fig. 4).

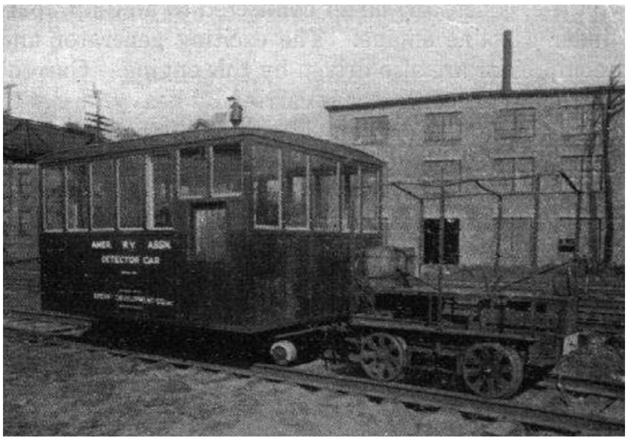

Fig. 4. One of the first carriages-defectoscopes in the world, developed by American Elmer Sperry in 1928 [39]

Defectoscopic equipment was housed on a cart in front of the cabin and the operator and recording device – in the cabin. Functional diagram of the defectoscope is shown in Fig. 5.

Rails magnetization was happened by passing through the rail of direct current of considerable size (up to 3.5 kA) at a voltage of 0.8 V. Sensors were represented by two coils of inductance (one for each thread of the track). Working speed of defectoscope does not exceed 20 km/h.

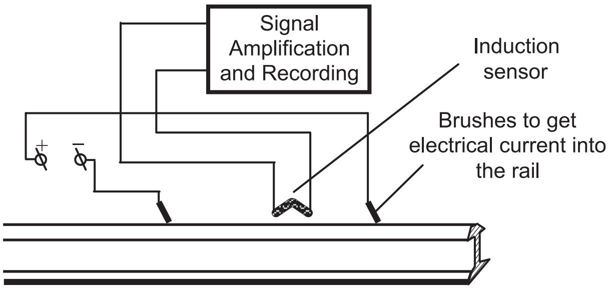

Fig. 5. Functional scheme of the carriage-defectoscope developed by Elmer Sperry [39]

After the successful defectoscope implementation into operation, in 1928 Elmer Sperry founded the company "Sperry Rail Service" [43], which exists to this day.

In the following defectoscopes "ARA" as a magnetization system powerful P-shaped direct current electromagnets were used and sensors placed behind the second (in the direction of motion) pole of the electromagnet, that is outside its magnetic field (operating mode by the method of residual magnetization of rails).

On the railways of USA and France also received significant distribution carriage-defectoscope of firm "Teleweld", which worked in the mode of the applied magnetic field, which was created (for each thread of the track) by the three powerful rod electromagnets. Defectoscope sensor consists of three pairs of local coils of inductance. The feature of this defectoscope was using of additional electromagnet, which created a weak alternating magnetic field of demagnetization of the surface layer of the rail to reduce the number of pulse signals, which correspond to safe surface defects of rails. The present carriage-defectoscope detects defects of the rails (outside joint overlays) at a speed up to 20 km/h.

In Russia the first magnetic carriage-defectoscope was released in 1933, which was developed by the inventor F.M. Karpov. In the design of F.M. Karpov, control and measuring equipment was used, which included [27]:

- magnetizing device with coils rigidly mounted on wheel pairs axles;
- search magnetomechanical sensors;
- devices indicating the presence of a defect in the form of lamps;
- system for recording signals from sensors in the form of a recording apparatus;
- device for marking a defective space on the rail.

The current in the magnetizing coils was served with a special contact-brush device. For the power of coils and other devices a diesel-generator of direct current with power of 15.5 kW was used. In this case, the generated magnetic induction in the rails was achieved 1.5–2 T, which provided magnetization of rails between the poles of the magnetization system to a state of saturation.

As sensitive elements magnetomechanical latches are used in the form of three arrow indicators. Under the influence of scattering fields of defects the arrows back and locked contacts, to which the relays of the executive circles were connected (lamps of light signalling recording apparatus, paint sprayer). It was possible to adjust the sensitivity of the arrows, which allows configuring them so that first reacted only on the defects of the affected area to 25% of section of the rail head, the second – from 25% to 50% and third – defects with an area of more than 50% – a kind prototype of automated classifier of defects.

All equipment was located on two railcars. The first served as traction and on it was installed power supply equipment. On the second was located control measuring equipment. The main difference of F.M. Karpov complex from similar foreign systems was that the sensors work in an active field, not by the method of residual magnetization. The speed of such a complex in working mode was up to 20 km/h. This circumstance predetermined its widespread distribution and to 1937 in Russia has already been used 4 magnetic carriages designed by F.M. Karpov. With their help annually tested about 2,000 km of the tracks and hundreds defective rails have been found. In F.M. Karpov railcar [27] with increasing speed more than 5–10 km/h on some sections of the track the noise level increased, which made it impossible to further control the state of the rails.

The first diagnostic systems of Elmer Sperry and Karpov led further to the rapid improvement of the mobile means of magnetic defectoscopy of railway rails. As a result of numerous research conducted in many countries, formed a separate method of high-speed magnetic diagnostics of railway rails, which was named – magnetodynamic method (MDM) [29].

3.1. Magnetodynamic Method (MDM)

This method, also known as Magnetic Flux Leakage (MFL) – «leakage of magnetic flux» or «scattering of magnetic flux», currently used in the UK, Iran, US and in the countries of the former Soviet Union for detection and characteristic defects of steel ropes, pipelines, railway rails, tanks and other industrial facilities of long-term and intensive operation [51]. Measuring two components of the magnetic field scattering: vertical (perpendicular to the study surface) and longitudinal (parallel to the applied field) are used in MDM systems [1, 33]. But using of only two components of the field scattering is ineffective, especially in cases where the form of the research object or defect with respect to the applied field is arbitrary. To do this, are already required to register all three components of the field, that is, there is a need for solving a three-dimensional problem. For this are require to register all three components of the field, that are needed in solving three-dimensional problem.

In 50–60's magnetic carriages-defectoscopes (MCD) appeared on the Soviet Union railways, which were developed by teams of specialists of ARIRT and Ural PTI and allowed to detect transverse cracks (defect codes 20 and 21 [40, 41] with an area of rail head defect from 25% and depth of 4 mm) at speed up to 70 km/h. In addition, these MCD reliably detected transverse and longitudinal cracks in the rails (defect codes 24, 25, 27, 30V and 30G), and rails fractures (codes 70, 74, 79) [40, 41].

Magnetization system of MCD consisted of two powerful magnets (one for each railway rail), which formed in the controlled area of rail magnetic flux to detect defects. At magneto-driving force (m.d.f.) of P-shaped magnetizing coils system 40 kA and the nominal size of the gap between the poles and rail 8-12 mm it forms magnetic flux from 7 to 10 mWb [29]. Much of magnetic flux formed by the magnetizing system is closed through carriages constructions and air and forms scattering flux, which allows getting a defectogram of the rail path. Signal sensor located on a search ski, which slides along the surface of the rail head during the movement of the carriage-defectoscope, registering the change in magnetic flux on the surface or subsurface defects. The introduction of computer registration of magnetic control signals [8] allowed improving the resolution of the system and detect defects in the weld and bolted joints connections of rails zone (types of defects 26.3 and 21.1), which previously had not been recorded by MCD during recording signals on magnetic film or paper tape.

In 70-80's in the Soviet Union about a hundred MCD are operated [29], which controlled the safety traffic of trains, timely detecting dangerous defects in the rails until they reach critical dimensions in the most adverse weather conditions (at temperature below -30^{o}C and high snow cover), when other methods were often unable to work [13]. Till now, according to [50], in countries that were part of the former Soviet Union about one hundred of the MCD by different modifications and complete sets have been operating. Their technical capabilities allow in the most diverse climatic conditions to control the upper part of the rail head to the depth of 7–8 mm at speeds from 20 km/h to 80 km/h. Carriages-defectoscopes operating experience also found their main disadvantages:

1. The existence of the air gap between the poles of a magnet and rail. The increase of this gap for the safety of the movement to 20–23 mm leads to

a significant weakening of the magnetic flux in the rail. Thus, by increasing the scattering flux clearly recorded all the structural elements of the rail track and the operator creates a false impression of the normal functioning of the complex, while the signals from internal defects of rails, that are available in MDM, are not fixed.

2. In classic carriages-defectoscopes between the poles distance is only 80 cm (for example, in the Lviv carriage-defectoscope № 442 distance between the poles is about 1 m) (Fig. 6). Such distance between the poles provides sufficient magnetization of rail in static mode [37]. However, at high operating speeds, the order of 60–70 km/h, the magnetic field does not have time to magnetize the rail at sufficient depth during the passage of the magnetizing system over its defective section. This is due to a significant increase of eddy currents in the rail with increasing speed of the movement of defectoscopic system.
3. Significant dimensions of electromagnets of rail magnetization system, which completely occupy the inter-wheel space of the induction carriage, and their energy intensity. Power consumption of electromagnets is approximately 15 kW.

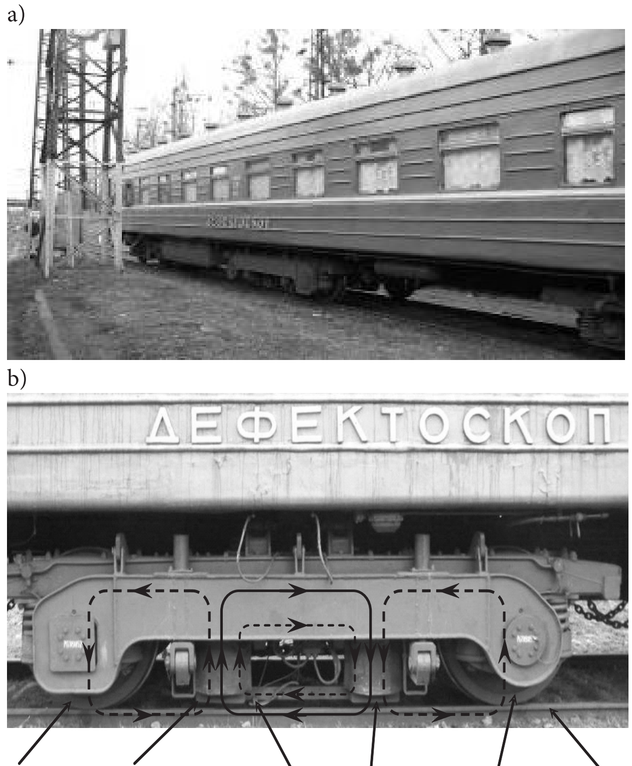

Fig. 6. Lviv carriage-defectoscope No. 442 for MFL diagnostics of rails defects [37]: a) general view of the carriage-defectoscope; b) view of the induction carriage and the magnetization system of the carriage-defectoscope

Eliminating or minimizing the impact of these disadvantages, according to the authors of article [37] can occur through the following changes:

1) cumbersome and energy-consuming magnetizing system based on electromagnets should be replaced by the magnetizing system based on modern permanent magnets through the wheel pairs of the induction carriage [28, 31];
2) receiving single-component system based on inductive sensors integrated should be replaced by the three-component multichannel system on the basis of point Hall sensors, which will allow implement the matrix and multicomponent rail sensors;
3) should be developed a new hardware and software part of the diagnostic system for the collection, transmission and analysis of defectoscopic information, which will provide the processing of multichannel defectoscopic information in real time.

The main advantages of mobile MDM defectoscopy, compared to ultrasonic, are as follows [37]:

1. Ability to contactless control of rails with a gap of 8–10 mm to the surface of the rail;
2. Reliability of control in a wide range of air temperatures and at high speed of movement of carriage-defectoscope.
3. Clear image on defectograms all regular structural elements of the track (bolted connection, insulated and welded joints, sleepers substrates, crosses, counterrails, arrow transfers, etc.) that provides an unambiguous setting of the defect position.
4. Working methods of test results decoding for the types of defects.

3.2. Metal Magnetic Memory Method (MMM)

It is a classical representative of magnetostatic methods and is known in the English literature as the name Metal Magnetic Memory. This method is actively developed and implemented in the high-speed diagnostics of railway rails [19, 20, 49].

MMM Method combines the potential opportunities of non-destructive control and fracture mechanics and, in this regard, has a number of advantages over other methods in the technical control of industrial objects. This method is based on the registration and analysis of the distribution of own magnetic scattering fields (OMSF) on the surface of the object in order to determine zones of stress concentration, defects, heterogeneity of the structure of the metal and welded joints.

MMM – it is an aftereffect, which manifests itself in the form of residual magnetization of the metal of the object and welded joints formed in the process of manufacturing and cooling in a weak magnetic field, or in the form of irreversible changes in the magnetization of the volume in zones of damages by stress concentration from workloads.

The main practical advantages of MMM Method in comparison with the known magnetic and other traditional methods of non-destructive testing the following:

- the application of the method does not require special magnetising devices, just as the phenomenon of magnetization of testing objects in the process of their operation is used, including the magnetization by the constant magnetic field of the Earth;
- the testing of objects can be carried out without the preliminary preparation of a controlled surface;
- small size recording devices with autonomous power can be used to perform the testing;
- the application of MMM allows to perform early diagnosis of fatigue damages and predict the reliability of the object.

The disadvantages of the method include:

- poor repeatability of results of inspections of objects in time;
- MMM Method can only be used to control ferromagnetic objects;
- the dependence of the level of measured signals on the position of the object relative to the vector of the magnetic field of the Earth.

MMM Method can be used for diagnostics of railway rail both in manual and in automatic mode. In the latter case, the equipment is located on the carriage-defectoscope [19].

3.3. Alternative Current Field Measurement technology (ACFM)

This technology is known in English literature under the name Alternative Current Field Measurement (ACFM) – «field measurement from alternative current». The Alternative Current Field Measurement technology was originally developed as non-contacting version of Alternative Current Potential Drop technology to accurately measuring the depth of surface-breaking fatigue cracks at welds underwater in the mid of 1980's. The ACFM first commercial systems were made in 1991 for underwater inspection of welded offshore structures. Since then, the technology has expanded into many diverse applications, both underwater and in air. In particular, these are systems for inspection of threaded connections in the mining industry, alternative inspection systems in the oil and gas industry, robotic systems for inspection of coke drum linings and latest complex semi-automatic matrix systems for high-speed railway tracks viewing [7–9, 10, 24–26, 47, 48].

The ACFM technology is an electromagnetic method, which allows detecting and sizing of surface breaking cracks in metals. The basis of the technology is that an alternating, locally uniform current is induced to flow in the component under test. The typical operating frequency is the order frequency of 10^4 Hz. Such current flows in a thin skin close to the surface of any conductor and does not depend on its geometry. When there are no defects present the electrical current will be undisturbed, but if a surface-breaking crack is present the uniform current is disturbed and flows around the ends and down the faces of the crack. Magnetic field above the metal surface, associated with the current, will also be disturbed.

The ACFM technology uses induced current instead of injected current with supporting of constant force and direction of current. This is the main difference of this technology from ordinary technologies of eddy currents. By measuring the components of the created surface-related magnetic fields and comparing the results with the theoretically forecasted ACFM allows determining the length and depth of the defect without having to calibrate on the standards. This provides the opportunity to both detect and classification of surface-breaking cracks in metals. Investigation does not need any electric or magnetic contact of sensors and study object and can be used without removing the surface coating (paint, varnish, oil, rust, etc.) or dirt. In this method, the signal level, when the sensor is removed from the sample, decreases in proportion to the square of the distance, and not the cube, as in the sensors on eddy currents. Due to this, the signals decrease relatively slowly, even when the sensor is detached from the surface at a distance greater than 5 mm. Thus, surface roughness or big thickness of non-conductive coating create less problems than at usual control with the help of sensors on eddy currents, which must be placed at a distance less than 2 mm from the investigated surface.

Fig. 7a demonstrates the power lines of uniform alternating current that flows at straight corner to the defect plane and the coordinate system to determine the directions of the components of the magnetic field induction.

The magnetic field induction component parallel to the surface and perpendicular to the current (marked as B_x) is proportional to the current surface density, which reduces at the centre of the crack and increases at the ends as the current flows around the crack. The size of the reduction in B_x is therefore indicating of the depth of the defect. The field component normal to the surface (marked as B_z) is generated by circulating current flows. These are found around the ends of the crack (clockwise at one crack end and anti-clockwise at the other), producing positive and negative signal levels. At that the distance between the B_z maximum and minimum signals is indicating of crack length. In order to estimate defect size the only two measurements required are the percentage reduction in B_x at the centre of the crack, and the distance on the component between the locations of the maximum and minimum values in B_z (Fig. 7b).

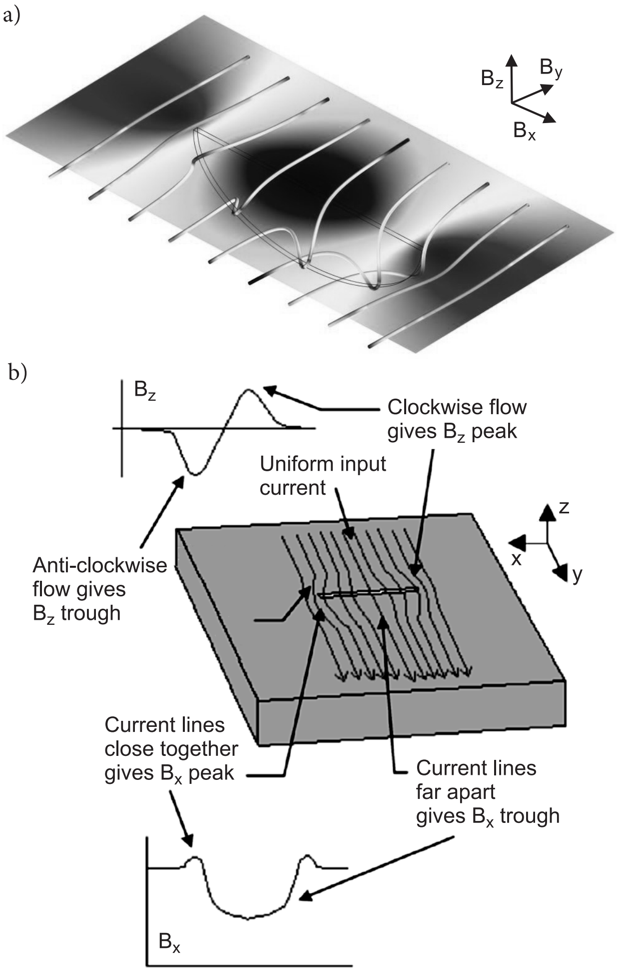

Fig. 7. Physical principles of ACFM technology [11, 26]:
a) uniform alternating current flowing around the defect;
b) components B_x and B_z of magnetic field induction created by the alternating current

A standard PC is used to control the equipment and display results. The plot on the left of Figure 8 shows typical raw data from the crack end (B_z) and crack depth (B_x) sensors collected from a manually operated probe. The right section of figure 8 shows the same data presented as a hodograph plot, in which B_x is plotted against B_z. In the presence of a defect, a loop reminiscent of a cardioid is drawn in the screen and the operator looks for the differences of its form from the typical to decide whether a crack is present or not. All data is stored by the system and is available for subsequent control and analysis.

The ACFM technology has also found its application and improvement in the railway industry for checking carriages, wheel pairs and rails.

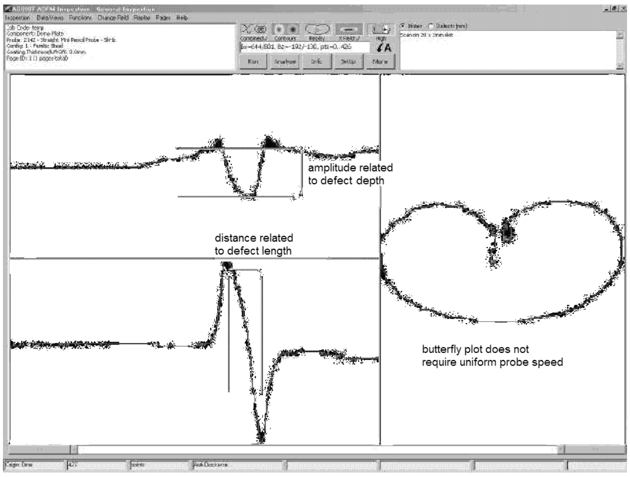

Fig. 8. Typical signal in ACFM, caused by a defect [26]

Carriages inspection is relatively easy since they are simply painted, welded structures, and inspection speed is not usually critical. Wheel pairs have a greater impact on traffic safety and more precise and volume trials were carried out, that ensure the reliability of results [7, 26]. The trials showed that ACFM outperformed some other methods (for example, magnetic particle inspection method (MPI)), particularly in terms of consistency of results. An EU-funded Framework 7 R&D SAFRAIL project (grant agreement No 218674) has resulted in the most advanced samples of ACFM array probes currently. Fig. 9, a shows the portable device developed for inspecting wheel pairs and an example of the results of a study of artificial defects This device contains a sensor block with 4 sensor pairs shaped to fit the radius at the wheel flange, and fourteen compliant plungers, each containing a additional sensor pair, to inspect the main part of the wheel, suitable even for large wheel wear to avoid lift-off of the sensors. During the tests on previously damaged wheel pairs the system reached 84% of defect detection compared to 44% their detection by the MPI method.

Following these successes, attention has turned to the sizing of RCF cracks on rails. Rail breaks from RCF cracking, particularly on bends, was a major problem in the UK in the 1990s. Inspection usually carried by visual review and by the ultrasonic portable inspection unit. Visual inspection gives no indication of the depth of any defects seen, while there was also a limit on the fact that ultrasonic sensors could not determine the size of the deepest defect if it was closely surrounded by shallower ones.

RCF defects have very different morphology to the standard fatigue cracks for which ACFM was developed. They are generally inclined at only 30° or so from the surface, but then may change direction to grow towards the surface leading to loss of part of

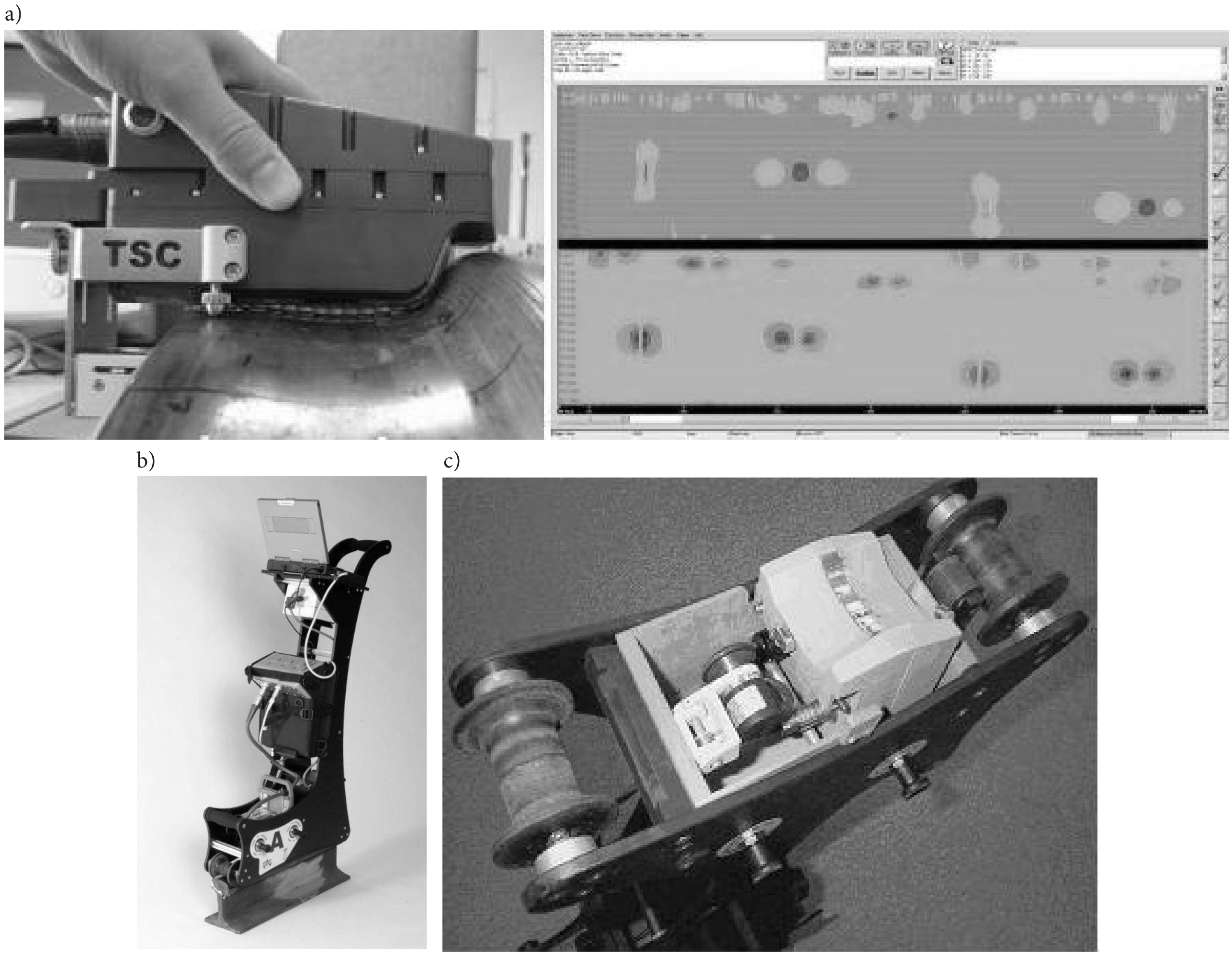

Fig. 9. ACFM technique [11, 26]

the rail surface, or conversely may form downwards rapidly through the rail leading to a rail break. In addition to this, the crack front will often be wider under the surface than on the surface, and crack depth will be large compared to its surface dimensions. All these factors mean that the theoretical sizing model developed in the 1980 s does not work for RCF cracks. To overcome this, lasting calibration trials were undertaken using rail with real RCF cracks. Results of sizing using the new calibration procedure were subsequently compared with other defective rails and generally good agreement was found [26, 48].

Special software incorporating the new sizing algorithm was produced. This software also included automated detection, and reporting of the deepest defect found in a given segment of the rail. An ACFM sensors array, shaped to the rail profile, was attached to a portable diagnostic system (see Fig. 9c), that also carried a modified high-speed Amigo instrument and laptop. This is a completely autonomous device that is capable of carrying out an 8-hour independent inspection of rails [26].

By increasing sampling rate to 50 kHz the portable diagnostic system achieved scanning speeds of 0.75 m/s (approximately – 3 km of rail can be inspected within an hour) (Fig. 9b). It should be stressed that sufficient data must be collected to not only detect a defect but also using special software to determine its severity [11].

Currently in the UK (companies Bombardier Transportation, TSC and Network Rail) further research is underway to speed up the data throughput and the operation of ACFM systems at high speed to allow deployment of ACFM on railroad vehicles such as road-rail cars (rail vehicles) and test trains, running at speeds between 15 km/h and 100 km/h.

ACFM sensors are available as standard pencil sensors and multi-element array sensors. ACFM pencil sensors can detect surface defects in any orientation. Nonetheless, in order to size defects, they need to lie between 0°–30° and 60°–90° to the direction of the probe movement. This disadvantage is overcome in ACFM arrays through the use of multi-directional magnetic fields and additional sensors, for the analysis of these fields in different directions. This is particularly useful in situations where the crack orientation is unknown or variable [26].

4. Visual-measuring and optical methods of mobile diagnostics

Until recently, a visual inspection was carried out only by experienced personnel, which walk along the railway track and physically looking for defects. This is a potentially dangerous practice, although it is often used by railway operators. Over the last few years, various video surveillance systems on the basis of visual cameras have been implemented for use on the railways [2, 11, 21]. They may be classified according to their functional purpose into four major groups:

1) track visual inspection systems;
2) train visual inspection systems;
3) systems for maintenance and operation;
4) passengers related systems.

The concept of automated visual systems is based on the use of a high-speed camera capable of capturing a video of the rail track when the train moves over it. The captured images are then automatically analyzed using the image analysis software. Software analysis is based on the identification of objects or defects detected using cross-correlation and wavelet transform methods, while data are classified using a supervised learning scheme and neural network theory. Object recognition by using test technology on samples is related to computational problems. To achieve real-time mode, the total duration of the calculations should be small. When trying to detect smaller objects, such as defects on the surface of the rail track, the resolution of the captured video needs to be high in order to provide reliable data for analysis. However, as the resolution of the video increases, the amount of received data increases, and, consequently, the duration of the calculation increases, which is necessary to complete the analysis. As a result, the speed of the inspection needs to be adjusted to match the data analysis speed.

Automated visual track inspection systems can be used to control and measure the rail head profile and the percentage of its wear, rail gap, displacement of sleepers, absence of part of the ballast (mineral bulk material between the sleepers and the earth's surface), base plate condition in absence of ballast, missing bolts of fastening and surface damage etc. The speed of operation of these systems can change from 60 km/h to 320 km/h depending on the type of inspection carried out and the resolution required. For example, inspection for the detection of rail corrugation can be performed much faster than that for the detection cracks from RCF. However, automated vision control systems do not provide all information regarding the presence of any internal defects and, therefore, can not be used to completely replace the ultrasonic inspection.

In the company Société Nationale des Chemins de fer Français (SNCF), in particular, operates with a high speed cameras inspection of its rail track network from new «IRIS 320» vehicle that can achieve speed up to 320 km/h. These inspections are performed every 15 days to detect visual surface defects over high speed lines as well as main lines (speed ≥ 160 km/h). On Fig. 10 show the principle of visual rail track inspection.

Similar systems are also developed in Germany (Bildverarbeitungssysteme GmbH) and in Italy (MERMEC). Their feature is the ability to provide a regular automated visual inspection of railway tracks with precise and early detection of defects and high processing speed. These visual-measuring systems can be used both for checking the whole surface of the rail and the absence of fasteners, sleepers and ballast.

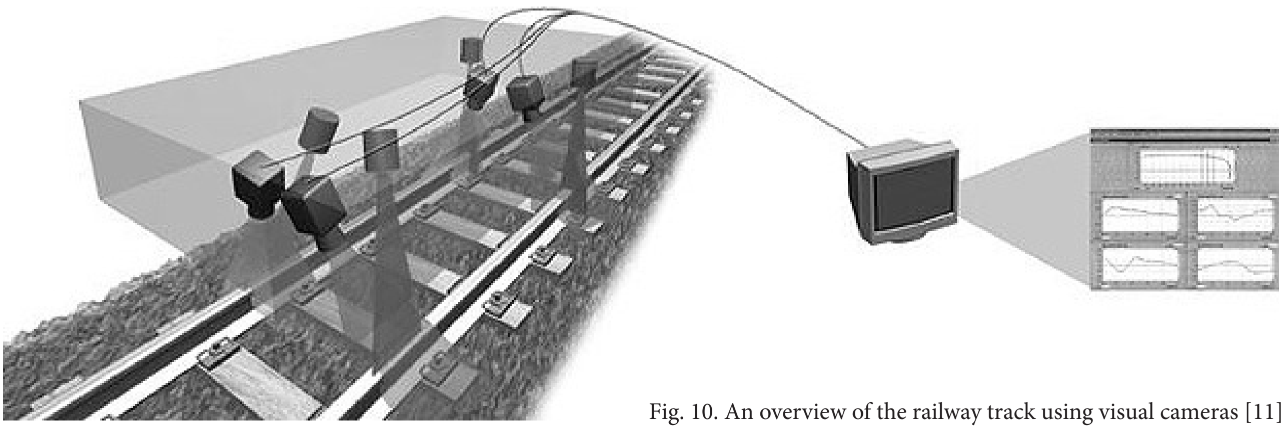

Fig. 10. An overview of the railway track using visual cameras [11]

5. Hybrid systems of mobile diagnostics of railway tracks defects

Recently, hybrid systems based on the simultaneous use of impulse sensors on eddy currents [14, 15, 38, 45, 46] and conventional ultrasonic sensors were introduced in Germany, the Netherlands and other countries for high-speed railway tracks inspection. Impulse sensors on eddy currents can accurately detect cracks of medium size (~ 4 mm) and can operate at speeds up to 72 km/h without significant differences in their work. However, the productivity of the eddy currents sensors depends to a large extent on the uniformity of the distance to the surface, which means that some surface defects may still be missed during inspection. For this reason, large-scale research is currently underway to develop a new high-speed equipment for hybrid systems for mobile diagnostics of railway tracks defects, including high-speed cameras, electromagnetic acoustic transducers (EMATs), ultrasonic phased arrays (UFA), ultrasonic lasers and multi-frequency eddy current sensors, other methods for the use of laser radiation (for example, Laser Scatterometry) and so on [11, 22, 23].

On the territory of the former USSR, research on the development of hybrid systems for mobile diagnostics of defects in railway tracks is underway. In particular, in Belarus JSC "Gomel VSZ" produces a combined carriage-defectoscope detectors based on a new type of passenger carriage (body model 61-537.1) (Fig. 11a) [6].

In the operator's room of this carriage-defectoscope are located: computer equipment, specialized defectoscopic complex, equipment for ultrasonic and magnetic information channels controlling and other specialized equipment. The power of this complex of equipment, as well as the defectoscopic magnetization system, is provided by a diesel-electric generator 13 kW.

The working speed of the carriage-defectoscope in at control of the railway track by the magnetic method is 60 km/h, but by ultrasonic method – 40 km/h.

Russian firm "TVEMA" (c. Moscow) from 2009 year manufactures carriages-defectoscopes of the new generation VD-UMT-1 (Fig. 11b), which are equipped with the newest means of ultrasonic and magnetic control (multichannel defectoscope «ECHO−COMPLEX-2») [3]. When carrying out the procedure for monitoring the state of the railway tracks defect detection is carried out by three methods of non-destructive testing – ultrasonic, magnetic and optical.

Magnetic method allows to control the presence of defects in rails, even at temperatures –50°C ÷ +50°C, since the work of ultrasonic defectoscopic systems is difficult at a temperature below –30°C because of the possibility of freezing contact liquid on the basis of water-alcohol mixture. The magnetizing system «MARS» with a powerful magnetic flux provides a deep magnetization of the rails, which allows to detect defects in the early stages of their development [3–4].

The carriage-defectoscope is equipped with a special wheel carriage with a hinged knot for constant contact of wheel pairs and rails, which ensures smooth movement in curved sections and arrow transfers. The positioning of the ultrasonic ski relative to the longitudinal axis of the rail head is ensured not by mechanical contact with the rail, but by the contactless magnetic method, which makes it possible:

- eliminate the mechanical contact of the centering system with the rail, which creates additional acoustic noise and reduces the resource of the centering system;
- minimize the dependence of the centering accuracy on the state of the working surface of the rail head;
- prevent disturbance of acoustic contact caused by snow falling between the rail and the ultrasonic ski;
- to ensure the passage of any arrow transfers;
- increase control speed.

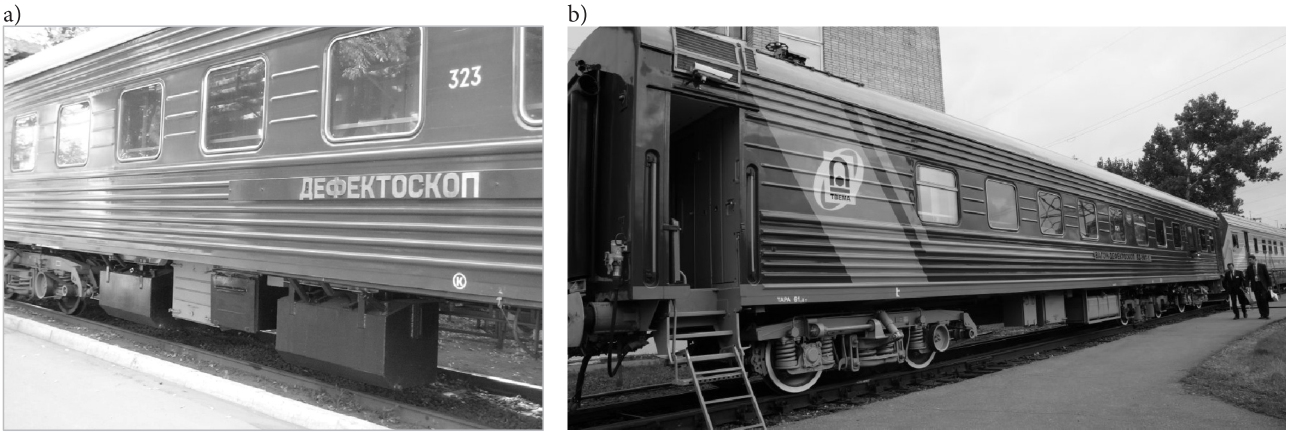

Fig. 11. Combined carriages-defectoscopes [3, 4, 6]

High-resolution linear video cameras and lighting system implement a system for visually identifying and measuring defects on the surface of the rails and their mounting elements («SVOD-2»), which automates and simplifies the monotonous process of continuous optical control and eliminates the "human factor", which reduces the probability of errors.

In 2015 year firm "TVEMA" began issuing even more modern carriages-defectoscopes VD-UMT-2 [4], which have the following advantages before VD-UMT-1:

- using of improved means and systems of complex non-destructive diagnostics (ultrasonic, magnetic, visual-measuring and optical);
- the possibility of implementing the overall speed of control to 60 km/h;
- extended climatic range of exploitation, etc.

In addition to the aforementioned control systems, a high-speed system for measuring railway track parameters «SOKOL-2» was used in this carriage-defectoscope and for receiving and processing the data on the state of the elements of the track in the carriage, a registering complex and specialized software «INTEGRAL» are used, which provides:

- the registration of data from the defectoscopic equipment about the state of the railway track elements, as well as about the current coordinates of the path and speed of the carriage-defectoscope;
- archiving and storing documents for control of all diagnostic systems.

System of automated processing of results of control «ASTRA» allows to carry out automated decoding of types of defects in rails, as well as other additional parameters of non-destructive testing technology. Also here is an additional system of observational monitoring of the state of the elements of the tracks.

In Ukraine, in the Institute of Telecommunications, Radioelectronics and Electronic Engineering of the National University "Lviv Polytechnic" for a long time the scientific group has been conducting research in the field of MFL defectoscopy using for the natural experiments of Lviv MCD No 442.

For laboratory studies MFL diagnostics of railway track an experimental stand specially developed in the institute is used, in which the primary magnetic field in the segments of defective rails is excited by powerful permanent magnets [30]. Appearance of the experimental stand is shown on Fig. 12.

As a result of the conducted researches, a working model of a fundamentally new multichannel component information diagnostic system was developed, which implements MFL diagnostics of railway rails based on Hall sensors [30, 32, 34-36, 42, 44].

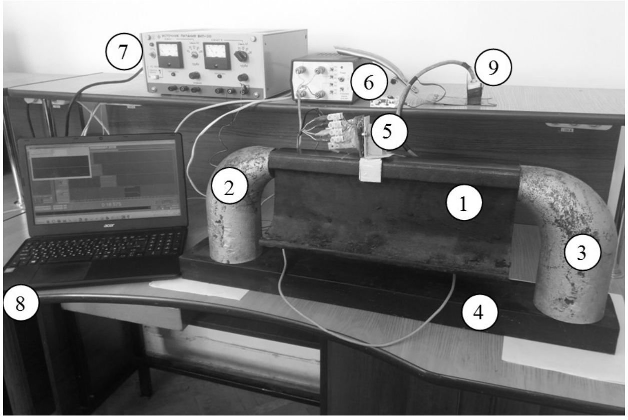

Fig. 12. Experimental stand for research of signals of the rails segments defects: 1) segment of the rail with the investigated defect, 2) and 3) poles of the permanent magnets, 4) yoke magnet conductor, which connects the poles of permanent magnets, 5) mobile carriage with Hall sensors and channel amplifiers, 6) analog-to-digital converter (ADC), 7) power supply, 8) computer, 9) induction integral sensor on a search ski from a magnetic carriage-defectoscope [own work]

6. Conclusions and outcomes

The analysis and comparison of modern methods and means of railway tracks defectoscopy allows us to conclude that despite significant advances in this area, the possibility of their further improvement is still possible.

In particular, in the area of the magnetic flux leakage method of defectoscopy, the possibilities for increasing the speed during the diagnostics, which largely depends on the parameters of the magnetizing system and its ability to magnetize the rail, are not exhausted. This is facilitated by an increase in the base between the poles of the magnets, with the possible control of the position of search sensors above the surface of the rail at the turns.

For reliable identification and differentiation of defect signals, it is necessary to increase the informativeness of the defectoscopic system through the use of multichannel and multicomponent sensors. In particular, the authors found that the vertical component of the magnetic flux leakage of the defect is also informative, and their compatible analysis enhances the reliability of detecting and discrimination of the defects. Further significant success in questions of the rapid detection of complex cracks with non-standard "bulk geometry" can be achieved by recording all three components of the magnetic flux leakage MFL of the defect – (3D magnetic field sensing for magnetic flux leakage defect characterization).

The use of multichannel systems for defectosopic information processing with the registration of three components of the signal of defect together with compatible analysis of the shape and amplitude of the signals on each channel will allow unequivocally to determine the approximate dimensions of the defect, localize its position within the intersection of the head of the rail and to classify the defect, will generally lead to a significant increase the effectiveness of the information defectoscopic system, including the detection of defects in the rails in the early stages of their origin and the establishment of their degree of danger.

The increase in the number of defectoscopic information significantly complicates the operator of carriages-defectoscopes work, which is quite tense and can cause an increase in the number of missed defects. This makes the task of developing special software tools for the automatic detection and discrimination of signals of the defects in real time. The algorithms for detecting and discrimination defectoscopic signals can be realized on the basis of compatible use the wavelet transformations and technology of neural networks in the analysis of signals of defects in the presence of a library of real defectoscopic signals.

Due to the wider application and implementation of the proposed measures of defects diagnostics in railway tracks, an increase in the reliability and efficiency of detecting signals of defects in the scanning process is expected with an increase in the speed of the carriage-defectoscope.

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