Optical diagnostics of railway rail defects

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Abstract. The safety of rail transport, including passenger traffic, largely depends on the timely diagnosis of the state of the rail infrastructure. To determine the state of metal structures, the method of acoustic emission (AE) is used. It is based on the registration of elastic mechanical vibrations arising in the material of the controlled object from a defect. The AE method is highly informative, but the interpretation of measurement results often causes difficulties, especially when studying complex structural elements. In this paper, it is proposed to use the digital image correlation (DIC) method to study the defects of railway rails using the acoustic emission method. Visualization of defects using the DIC method will make it possible to better interpret the results of inspection by the acoustic emission method and to establish the relationship between the size of defects and the parameters of AE pulses.

1. Introduction

Fatigue fractures of critical parts of the rolling stock, such as railway rails, are one of the main factors of train derailment. Despite the existence of various physical control methods (eddy current, ultrasonic, magnetic), the causes of accidents are, as a rule, missing defects in various railway facilities. In addition to the obvious reasons associated with the influence of the human factor, missing defects can be explained, firstly, by a wide variety of geometric shapes and sizes of controlled elements, and secondly, by a rather low sensitivity to the detection of unfavorably located crack-like defects, which is inherent in traditional methods of control.

In this regard, the method of acoustic emission (AE) is promising for detecting dangerous crack-like defects in rails [1–3]. Unlike other methods of non-destructive testing, such as ultrasonic or radiation, a defect in the AE method is revealed not as a violation of the continuity of the material, but as a source of elastic mechanical vibrations when the controlled object is loaded. Because of this, the acoustic emission method is less sensitive to the orientation of the defect in space and location. At the same time, at the stage of developing the technology of acoustic emission control of specific products, it is necessary to first establish a clear relationship between the size and location of the defect and the parameters of the received acoustic signals.

In this work, a study is carried out on the possibility of detecting crack-like defects in railway rails using the method of acoustic emission. To obtain information about the parameters of a defect, the DIC method (Digital Image Correlation) [4–6] is used in the work, which makes it possible to determine with high accuracy the actual dimensions of rail defects. The combined use of AE and DIC methods at the stage of developing the technology of rail flaw detection will make it possible to
establish a relationship between the parameters of defects and acoustic emission signals [7–8]. In the presence of such a relationship, the results of measurements by the acoustic emission method will be correctly interpreted, which will make it possible to use the AE method when monitoring natural objects.

2. Investigation method

The R43 railway rail was chosen as the object under study. Samples for testing were rail fragments 10 ± 1 mm thick. After cutting, the surfaces of the cuts were subjected to milling and grinding to obtain the required quality of the end surfaces. On the cut fragments, thin cuts were made over the entire thickness of the rail at a given depth, simulating a defect. The notches were made by machining on an electric discharge machine using a wire of 0.25 mm diameter. The width of the finished cut is about 0.25–0.3 mm. The notch depth is 2–4 mm, depending on the sample. The location of the notch also depended on the sample – either the rail neck or fillet transitions from the rail neck to the head and from the neck to the sole. A photo of one of the rail fragments is shown in figure 1(a). To increase the contrast of the investigated surface and improve the measurement results using the DIC method, a random pattern was applied to one surface of the samples using aerosol paints of white and black colors (figure 1(b)). A fatigue crack of a given length was grown on the notched rail fragments with paint applied to the surface. For this, the fragment was installed in the grips of the Instron 8801 testing machine by the end surfaces (figure 1(c)–(d)) and a smooth cyclic loading was carried out by stretching with a sinusoidal cycle with a frequency of 10 Hz and a cycle asymmetry coefficient $R = 0$ (pulsation cycle). The lengths of the finished cracks were 0.5–4 mm.

![Figure 1. Photo of a fragment of a rail after machining (a); after applying aerosol paints (b); in the grips of the testing machine while growing a crack (c, d).](image)

Testing of rail samples with a notch and fatigue crack was carried out on an Instron 5982 universal testing machine in the compression loading mode. A photo of the test setup during testing is shown in figure 2. The loading of the samples was carried out by cyclic compression according to a programmed cycle that simulates the passage of a car at a low speed (about 3–4 km/h). Each rail was loaded with three such cycles. The test was repeated several times (usually 7–10 times).

Registration of acoustic signals during the tests was carried out using the industrial system A-Line 32D. The measuring path consisted of PAEF-014 resonant transducers and preamplifiers of the electrical signal. The intrinsic noise of the equipment, preamplifier and AET was 26 dB. The acoustic noise level after placing the sample in the grips of the testing machine was 34 dB.

The DIC (Digital Image Correlation) method was used to measure the deformation of the test samples. It is based on digital processing of images of the surface of a deformable sample. Surface
images are recorded using a video camera or several video cameras to measure three-dimensional deformations. Further, the images are divided into small sections, for which their movement is tracked in the images obtained under various loads. The offsets of the regions allow you to evaluate the deformations occurring in the surface, and thus in the entire sample. A correlation function calculation can be used to find the offsets. However, in the presence of plastic deformations, this approach cannot be applied directly, since the same surface area under different loads will change due to deformations. Therefore, one of the most common approaches in the DIC method is the LSM (Least Squares Matching) algorithm. The algorithm consists in the selection of the parameters of the affine transformation of the original area of the image for maximum coincidence with the area in the image with loading.

![Image]

**Figure 2.** Photo of a test setup with acoustic emission sensors attached to a sample during tests of rail fragments.

We used a LaVision StrainMaster measuring system consisting of two Imager SX video cameras, a synchronization device for simultaneous acquisition of LaVision PTU images, and a personal computer with DaVis 8.4 software. The cameras have a maximum resolution of 4 megapixels, and a shooting speed of up to 17 fps with a bit depth of 12.

3. Experimental results
Figure 4 shows the AE data on amplitude-duration correlation diagrams. The diagrams are given for several samples with different defect sizes. For the same samples, the results of processing experimental images by the DIC method are presented. In the pictures with images, the displacement vectors correspond to the displacements of the sample surface areas. The offset is calculated between the first frame in the series, when the sample is not loaded, and the current frame. The color in the figure shows the amplitude of strain. The real value of the deformation in the results is much less than the magnitude of the vectors. This is due to the elastic deformation of the testing machine, its bed, grips, rods, force-measuring device and other parts. To determine the true displacement in the software, it is possible to use a virtual strain gauge, which allows you to measure the distance between any two points on the surface.

From the data presented in figure 4, it follows that the parameters of the AE pulses depend on the presence of a defect and correlate with its size. For example, for defect-free samples (figure 4(a)), a small number of AE pulses with a duration of no more than 2 ms and an amplitude of no more than
75 dB are recorded, the presence of a defect leads to the appearance of pulses with an amplitude of more than 75 dB and a duration of more than 10 ms (figure 4(c)), while a correlation appears between the amplitude and duration; for more extended defects, pulses with an amplitude of about 100 dB and a duration of about 30 ms are recorded (figure 4(f)).

Figure 4. AE (a), (c), (e) and DIC (b), (d), (f) inspection results for samples with different defect sizes: (a), (b) – defect-free sample; (c), (d) – sample with 2 mm notch, 1 mm crack; (e), (f) – sample with 4 mm notch and 2 mm fatigue crack.
The processing of the obtained images made it possible to establish the exact dimensions of the defects – notches and grown fatigue cracks. The crack opening near the tip can be very small (less than a micron), and due to imperfect surface preparation, the exact crack length is difficult to detect by visual measurement methods, including optical microscopy, even at high microscope magnifications. For the same reason, it is difficult to use physical control methods based on the penetration of substances into the defect – due to the small opening, the magnetic particle flaw detection method does not allow to reveal the crack length accurately. The use of the DIC method, due to the continuous recording of displacement fields during loading of the sample, makes it possible to estimate the size of the defect more reasonably compared to visual measurement methods. The results obtained made it possible, based on the test results of 25 samples, to reveal the relationship between the parameters of acoustic emission signals and the size of defects in the test sample.

4. Conclusion
The paper presents the results of laboratory tests for the strength of railway rails using the method of digital image correlation and acoustic emission. The possibility of visualizing fatigue cracks in the test specimens is demonstrated. It is shown that the use of the DIC method allows one to accurately identify and estimate the linear dimensions of defects arising in the rails, and to estimate the distribution of deformations in the rail section under its loading.

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