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CROSS-CORRELATION FUNCTION IN IDENTIFYING HEAD CHECKING DEFECTS OF THE RAILWAY RAILS

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Abstract

The cross-correlation function has been applied to the study of the similarity of the two functions. One of these functions is known and represents a defect type HC (Head Checking) in the railway rail. The second function is unknown and based on cross-correlation function of both functions specifies the parameters of the similarities. These functions correspond to defects whose images have been determined using laser scatterometry method. FFT method has been used to calculate these functions.

Key words: cross-correlation, railway rails, defect head checking, laser scatterometry method

FUNKCJA KORELACJI WZAJEMNEJ W IDENTYFIKACJI WAD HEAD CHECKING SZYN KOLEJOWYCH

Streszczenie

Zastosowano funkcję korelacji wzajemnej do badania podobieństwa dwóch funkcji. Jedną z tych funkcji jest znana i stanowi opis wzorca wady head checking (HC) w szynie kolejowej. Druga funkcja jest nieznana. Na podstawie funkcji korelacji wzajemnej obu tych funkcji, określa się parametry ich podobieństwa. Funkcje te reprezentują obrazy wyznaczone doświadczalnie, metodą skaterometrii laserowej. W obliczeniach wykorzystano szybką transformatę FFT.

Słowa kluczowe: korelacja wzajemna, szyny kolejowe, wada head checking, metoda skaterometrii laserowej

1. INTRODUCTION

Detection of defects in railway rails and prevention of their development are important elements in the development of modern railways. This is especially true in turn to the great speed trains. Head checking (HC), squats and shelling are the most common disadvantages of Rolling Contact Fatigue type [4], [14]. This paper is concerned with the testing defects of head checking.

HC defects although they look inconspicuous, can lead to cracks and fractures of the rails [6]. Typically, micro-cracks arise and they are visible on a considerable length of the rail. They are almost parallel, close to each other, and their length is 10 – 15 mm. This phenomenon is caused by lateral contact force and geometrical spin. Disadvantages of HC in the heavily advanced form are shown in fig. 1. Fig.1a also shows the section of the rail with HC defects made with the use of the laser. These defects are in the shape of straight grooves whose width and interval is 100 µm - 850 µm and 50 µm., respectively. Fig. 1b shows the path of the laser beam by which it is probed at the appropriate points and receives further images from the article.

In most countries railway authorities usually use ultrasonic, magnetic and visual methods to detect HC defects. In order to classify and assess them, authors used methods presented in [2], [3], [7], [8], [9] and [10]. In this paper, the unique laser scatterometry method [6] which has not yet been applied to detect HC defect in the railway rails has been presented. This method also allows for squats detection [5].

2. PRINCIPLE OF CROSS-CORRELATION

Calculations of contour circuits for measurements of defects images have been made in an accordance with the Eq. (1) [6]:

$$\overline{O}_W = \left(aN_B - bN_W\right)\Delta x \tag{1}$$

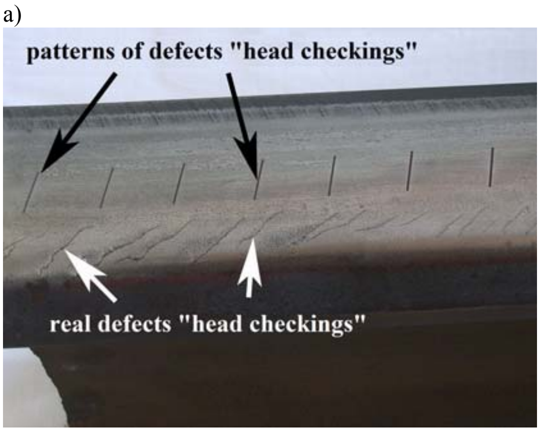
where: N_B – denotes the number of elementary sections with length, which bring near the contour, N_W – denotes the number of vertices of the polygon described on the contour, with sides:

$$a = \frac{\pi\left(1+\sqrt{2}\right)}{8} \approx 0.948 \qquad b = \frac{\pi}{8\sqrt{2}} \approx 0.278 \tag{2}$$

where: the coefficients a and b are chosen to minimize the variance of the error straight sections of all possible angles and providing zero mean value.

Contour circuits reflected from the running surface between reference defects were in the range from 722 to 896 pixels. While on the surface rail, between actual defaults, contours of reflected circuits were less and they were within the range from 472 to 666 pixels. This means that the roughness of the surface is greater.

a)



b)

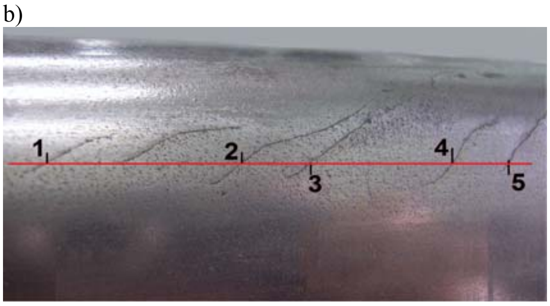


Fig. 1. The tested rail: a) with patterns and real defects, b) with scan way on real disadvantages signed in turn from 1 to 5

Safety and comfort of traveling by train resulting from previously diagnostics and prevention such a flaw has been described in many papers [4], [12] and [13]. Now research works are carried out, the objective of which is the development of effective methods for detection of surface defects. Hence the proposal for the application of the method cross-correlation function for testing.

Laser scatterometry method uses the phenomenon of reflection of laser light from variety surfaces. It has been described in several papers, for example [5], [6]. Reflection of light in a way where the whole undiluted laser light beam after the reflection only changes the direction of keeping the same angle of incidence and reflection, testifies to the perfectly smooth surface. Rough surfaces force different behaviour of beam after reflection (there is even the full dispersion of light) [1], [11].

Perfectly smooth rolling surface of rail in fact does not occur. That's why we accept, that dominate mirror reflection, but also there exist diffuse beams. Cracks, faults, splinters, folds, etc. cause also changes the behaviour of the reflected beam. Therefore, information about the behaviour of the laser light after reflection from the surface of the rail, is the basis for its evaluation [12], [13].

Cross-correlation of the two functions is:

$$c(x,y)=f(x,y)\otimes g(x,y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(s,t)g^{*}(s-x,t-y)dsdt \quad (3)$$

where the asterisk denote the complex conjugate. The cross-correlation can be easily calculated, if it takes into account that the Fourier transforms of both sides of the equation (3) is:

$$C(\nu_x,\nu_y)=F(\nu_x,\nu_y)G^{*}(\nu_x,\nu_y) \quad (4)$$

where C, F, and G are the Fourier transforms of the functions c, f, and g. If function g contains the pattern that it wonts to search for in the distribution function f, then the cross-correlation function shows "peak" in this place, where it occurs. In the absence of similarity, cross-correlation function is fuzzy and weaker. "Peak" indicates that the spatial frequencies that occur in the reference image are reinforced. Spatial frequencies, which do not occur in the pattern are eliminated.

For a quick calculation of the cross-correlation function it can therefore apply the algorithm of the Fast Fourier Transform (FFT). Because there are few functions with exact Fourier transformation, so to use this tool to analyse any of the functions, the need is for certain assumption. First of all, it must be assumed that the test function is recursive, i.e. the test sample is repeated an infinite number of times in both dimensions, and the analysis we choose only one period of variation in both dimensions. Then the equation for Fourier transform:

$$F(\nu_x,\nu_y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\exp[2\pi i(x\nu_x+y\nu_y)]dxdy \quad (5)$$

can be presented in a form convenient for numerical computations as Discrete Fourier Transform (DFT) [15]:

$$F(k,l)=\sum_{-N}^{N}\sum_{-M}^{M} f(n,m)\exp[2\pi i(n\Delta xk\Delta\nu_x+m\Delta yl\Delta\nu_y)] \quad (6)$$

where $\Delta x,\Delta y$ are the distances between adjacent sampling points in the direction of the x axis and the y and $\Delta\nu_x,\Delta\nu_y$ are the distances between adjacent sampling points in the spatial frequency plane. To apply the FFT algorithm, we should assume that:

$$\Delta x=\frac{1}{(2K\cdot\Delta\nu_x)},\Delta y=\frac{1}{(2L\cdot\Delta\nu_y)} \quad (7)$$

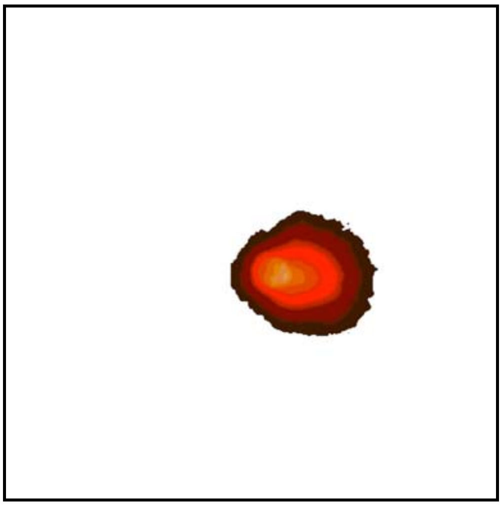
$$\Delta\nu_x=\frac{1}{(2N\cdot\Delta x)},\Delta\nu_y=\frac{1}{(2M\cdot\Delta y)} \quad (8)$$

where $(2N + 1)$, $(2M + 1)$ mean the number of sampling points in the object plane, while $(2K + 1)$, $(2L + 1)$ – the number of sampling points in the Fourier plane.

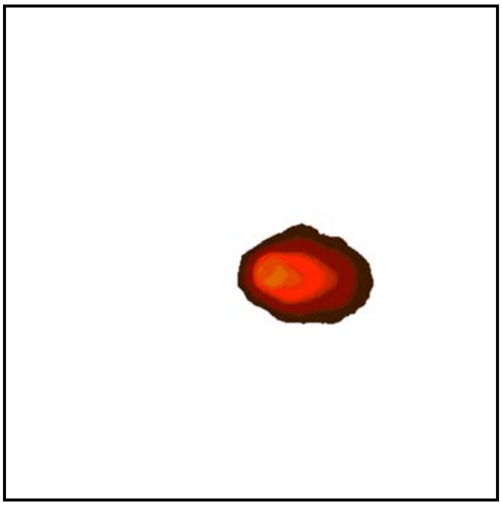
3. CROSS-CORRELATION FUNCTION OF THE REAL HC DEFECTS

The idea of this method is to compare an unknown function to a pattern that represents the "perfect" defect. If there is similarity of the distribution to the pattern in the image it can be seen a clear "peak". Fig. 2 shows the images of the dispersion of the laser beam from defect type "head checking" shown at the upper part of Fig. 1a.

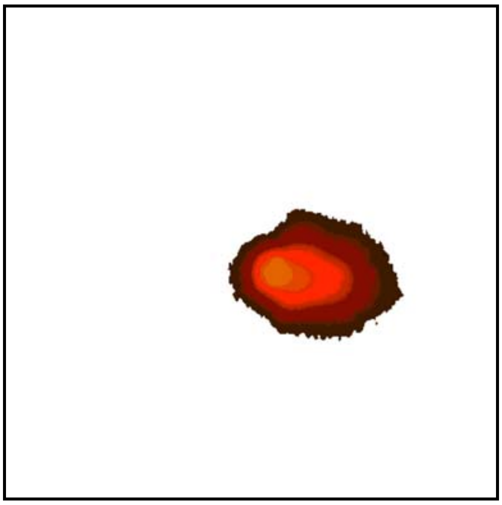
a)



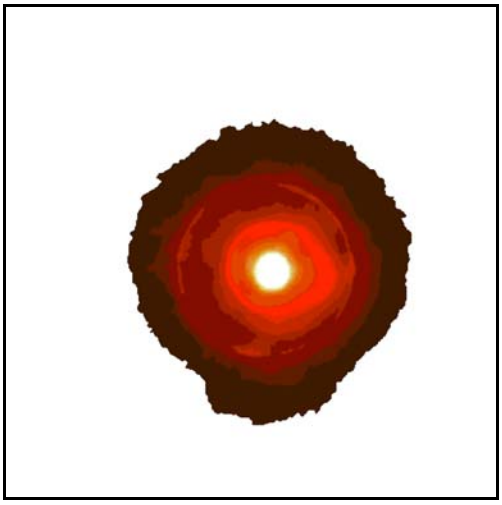
c)



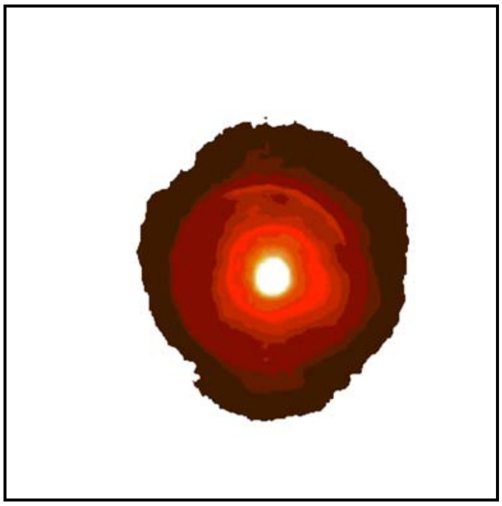
e)



b)



d)



f)

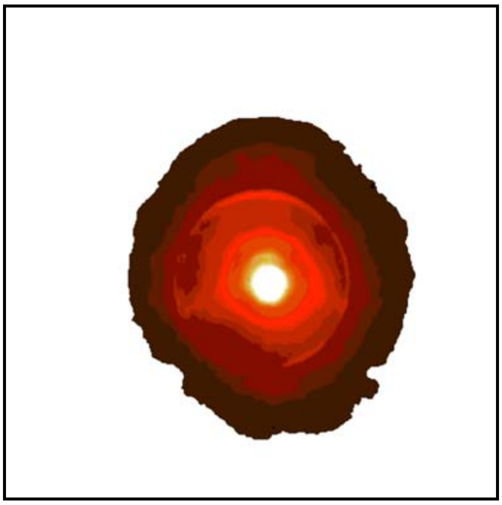


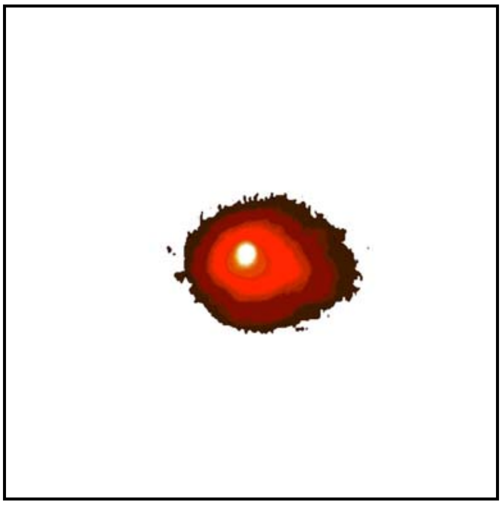
Fig. 2. Images of the dispersion of the laser beam: (a), (c) and (e) show the HC pattern of defects, in width 500, 650, 600 μm, from Fig. 1a, (b), (d), and (f) show the rolling surfaces, and they came from grinded head of the rail

The further calculations regard Fig 2b, 2d, and 2f as rolling surfaces.

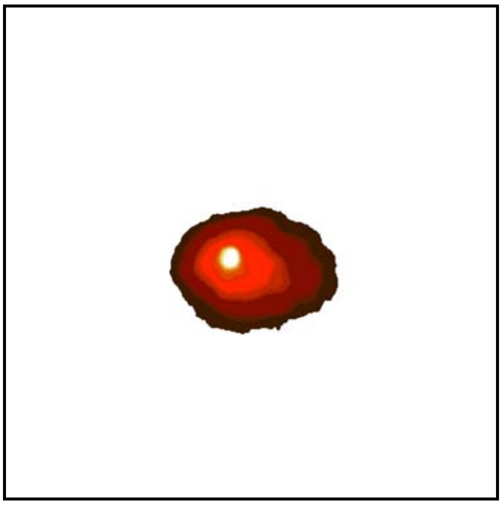
In the Fig. 2 it can be seen that the laser beam dispersion occurs even if the beam reflects from the rolling surface without defects. It can be seen that the beam reflection are different in nature depending on what surface to reflect. In this figure there are the functions that will be used as a pattern in studies the similarities to the functions unknown.

Fig. 3 shows the distributions dispersions of the laser beams originating from unknown defects.

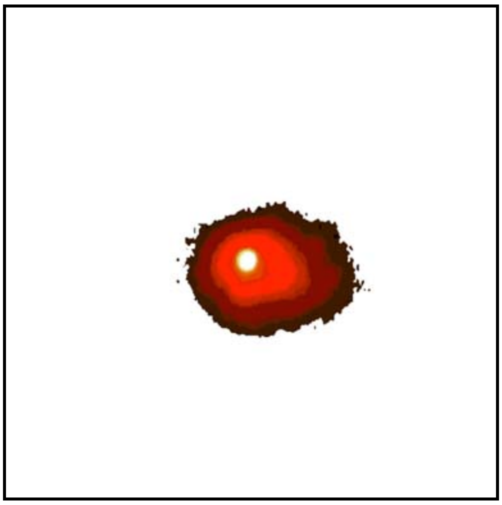
a)



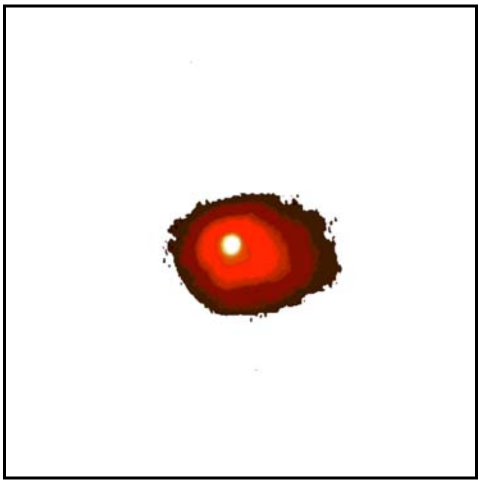
b)



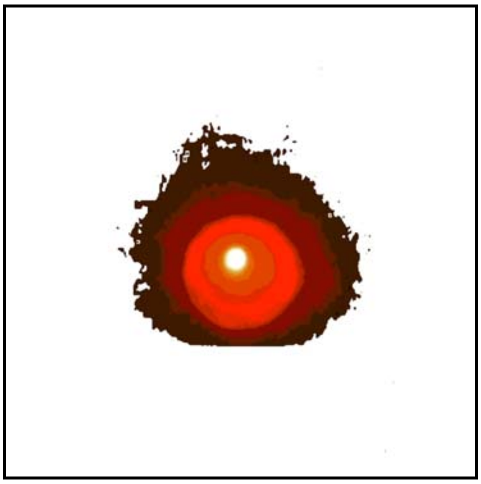
c)



d)



e)



f)

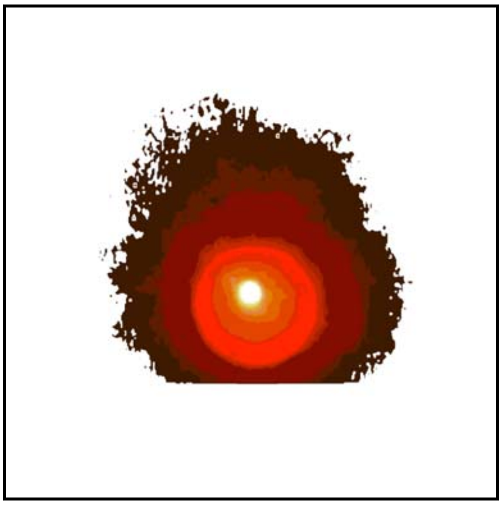
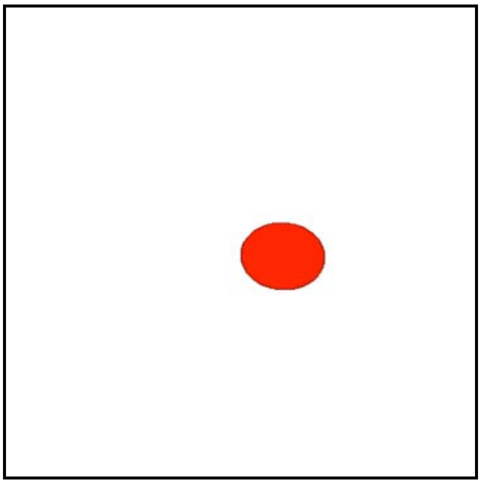


Fig. 3. Images of the dispersion of the laser beam: (a), (b), (c) and (d) show the unknown defects, corresponding to the 1 – 4 HC defects from Fig. 1b, (e) and (f) show the rolling surfaces of the rails of Fig. 1b

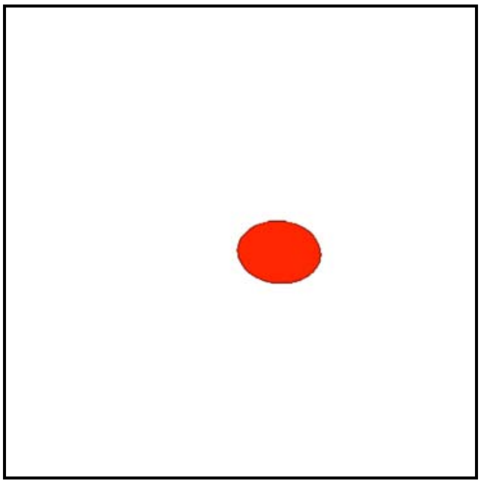
4. CALCULATIONS

To calculate the distribution of the cross-correlation function, it should performs the calculation of double integral, which itself is a function of two variables. In these calculations, to speed up them, it can use the Fast Fourier Transform (FFT) algorithm. To do this, it should first calculate the Fourier transform of the functions f and g. Then it can calculates the multiplication of the function F and the complex conjugate of G, and then calculates the inverse Fourier transform of the multiplication. A graphical representation of these calculations are presented in Fig. 4.

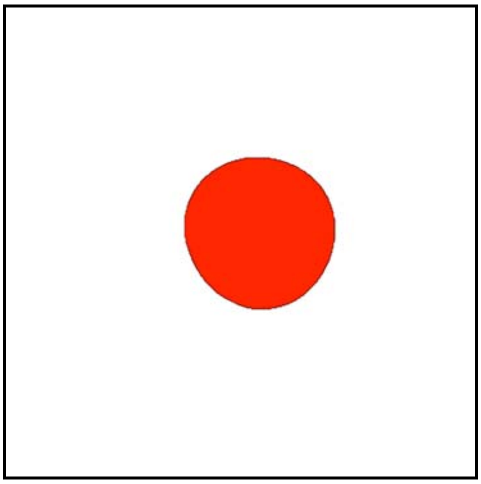
a)



b)



c)



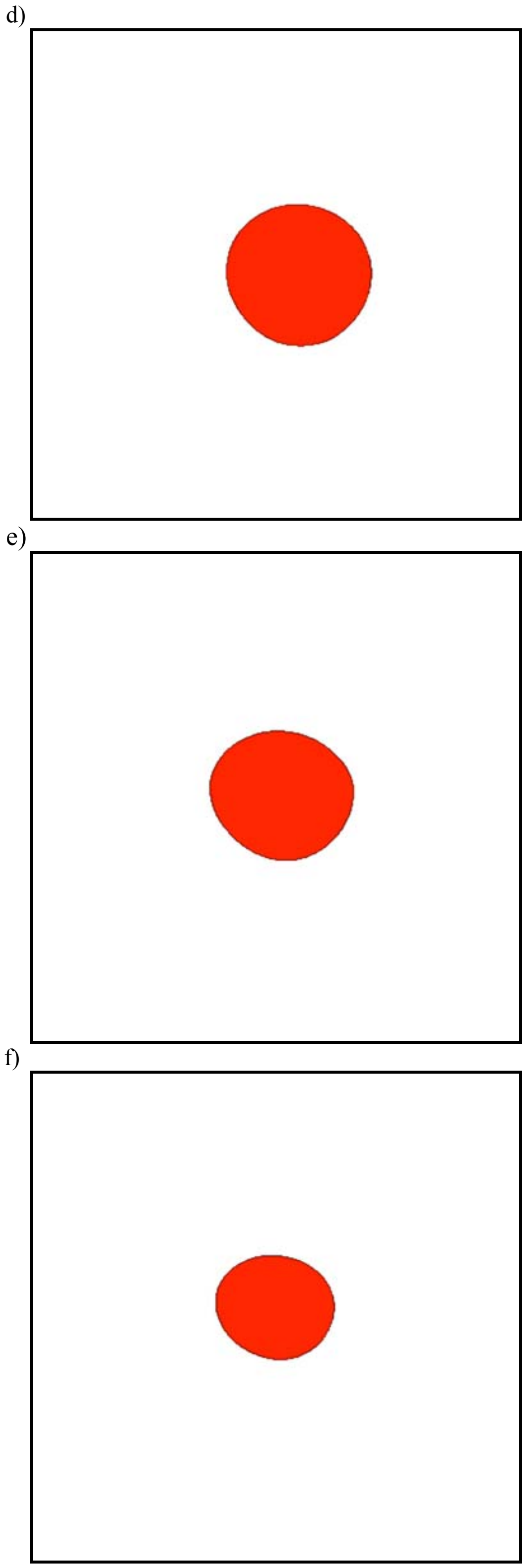


Fig. 4. The images of cross-correlation functions: a) of Fig. 2a and Fig 3a; b) of Fig 2c and 3c; c) of Fig 2e and 3d; d) of Fig. 2b and 3e; e) of Fig. 2d and 3f; f) of Fig. 2c and 3f.

Fig.4a, 4b and 4c show cross-correlation function of real HC defect and the patterns. Fig. 4d and 4e show cross-correlation function of rolling surface and the pattern of rolling surface. Fig. 4f shows cross-correlation function of the pattern and the real rolling surface.

As for images captured using a CCD camera it is very difficult to tell the difference in intensity of images recorded in two independent processes. Therefore, such images can only roughly determine whether features compared are similar or not. It is different in the case of registration of images on a photographic plate. There are applied holograms so that it can register multiple images at once. With such a hologram one can easily read that the distribution has a greater intensity and one can be seen at once, "eye" whether the two distributions are more alike than others. So there is done in one process and the images are recorded on the same film, as in the case of Vander Lugt filters [16]. Vander Lugt filters are used in the optical information processing. Then it can on the basis of several images determined their similarity to the standard. In the case of image registrations in several processes, it is necessary to perform additional calculations. In the case of distributions recorded by CCD camera the situation is different, especially that each image is recorded on a separate picture. On the same image one cannot be read, which has the largest distribution. of intensity. If the image composed of many elements often repeated, then this method can be successfully used in the study, because all these elements are in one image. In place of the element sought we would get a clear "peak". Therefore, when the image we have a single distribution and is compared to another, it must be used another method. If the individual intensity distribution is registered, the binarization process is to divide all values in the intensity at 256 intervals corresponding to 256 grey levels in the distribution. This procedure results in some cases, the intensity values converge comparing two different distributions, despite the difference between them. Such a method has advantages because the two distributions may vary in intensity, they can still show a high degree of similarity. In contrast, how it affects the way of binarization on the results, it is appropriate to carry out calculations, which undoubtedly will publish in subsequent publications. Our proposal is based on cross-correlation function and autocorrelation function of the two distributions to determine their similarity.

The function like:

$$s = \frac{\max\limits_{x'y'} \left| \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} f(x,y) g(x-x', y-y') dxdy \right|}{\max\limits_{x'y'} \left| \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} g(x,y) g(x-x', y-y') dxdy \right|} \tag{9}$$

riches maximum when g = f. Because the functions f and g are real so the integral (9) also is real. We assume that the functions f and g are continuous and integrable in the space R^2. Then the expression (9) makes sense. If the norm of real function refer to as

$$\|f(x,y)\| = \sqrt{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f^2(x,y)\,dxdy} \qquad (10)$$

and

$$\|g(x,y)\| = \sqrt{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g^2(x,y)\,dxdy} \qquad (11)$$

then we say that the functions f and g are normalized. If the expression (9) is to be set in the range of $0 \le s \le 1$, then we must assume that

$$\|f(x,y)\| \le \|g(x,y)\|. \qquad (12)$$

This means that the norm of the function f is not greater than the norm of function g.

For the calculation formula (9) need be converted some. So we really have given distributions functions f and g in a grid 400×400 points and make numerical calculations on this grid. Formula (9) for numerical calculation takes the following form:

$$s' = \frac{\max\limits_{k,l} \sum_{i=-N}^{N} \sum_{j=-M}^{M} f_{ij}\, g_{i-k\, j-l}}{\max\limits_{k,l} \sum_{i=-N}^{N} \sum_{j=-M}^{M} g_{ij}\, g_{i-k\, j-l}} \qquad (13)$$

where the summation extends over the entire grid of points, ie. i = -200, ..., 0, ..., 200 and j = -200, ..., 0, 200. Similarly maximum is taken across the grid, ie. k, l = -200, ..., 0, ..., 200.

In the Tab.1 are presented the results obtained by using the expression (13). It shows the degree of overlap of master HC images and real HC defects. Based on this table, it can see that the images 2c and 3c are very similar. Also, images 2e and 3d and 2d and 3f are similar. This means that the defect shown in these images is likely to be of the same type.

Tab. 1. Values of overlapping of functions (expression (13)) for images showed on Fig. 4.

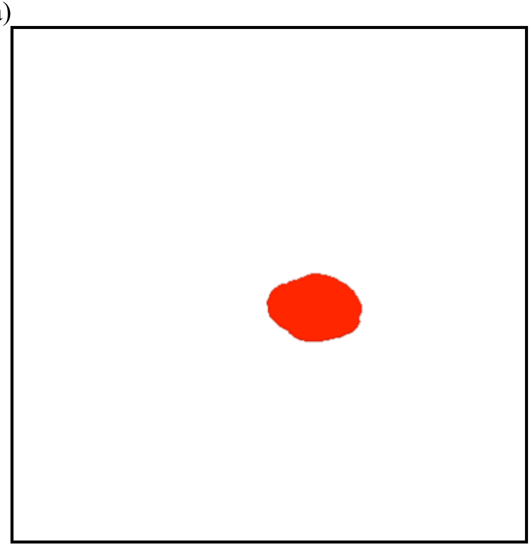
Image	Overlapping of functions (expression (13))
Fig.4 (a) - (Fig. 2a and 3a)	64.70 %
Fig.4 (b) - (Fig. 2c and 3c)	84.93 %
Fig. 4 (c) - (Fig. 2e and 3d)	83.6 %
Fig. 4 (d) - (Fig. 2b and 3e)	65.7 %
Fig. 4 (e) - (Fig. 2d and 3f)	82.8 %
Fig. 4 (f) - (Fig. 2c and 3f)	16.6 %

However, images 2a and 2b and 3a and 3e have a similar medium, which means that defects on them may belong to the same class. In turn, 2c and 3f images are not similar to each other. This means with great probability that the defects showed in these images belong to different classes.

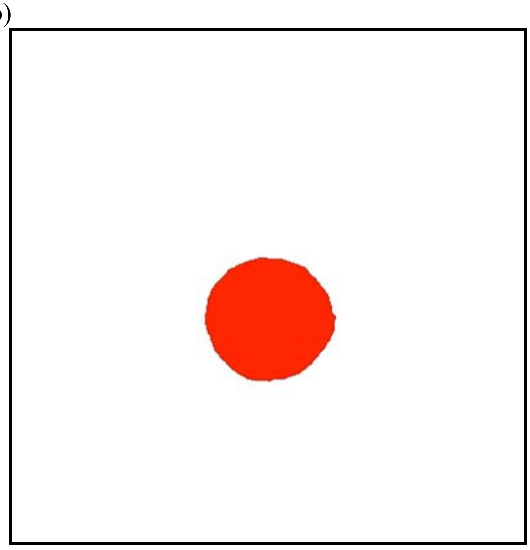
With the Tab. 1, it can be seen that the images of HC patterns of the same types as the images of the real HC defects are similar. The last entry in the Tab. 1 shows that the images of HC patterns and the images of real HC defects of different types are clearly different. This suggests that this method can be used for the automatic classification of defects in train rails. Perhaps the formula (13) does not cover all cases and the need to develop a different algorithm, but these are initial studies of defects type HC.

Fig. 5a), b) present binarized images after performing the binarization at the threshold level equal to 178 pixels for images from Fig. 2a), b). Additionally, Fig. 5c),f) show images after calculating cross-correlation function for images from Fig.5a), b).

a)



b)



c)

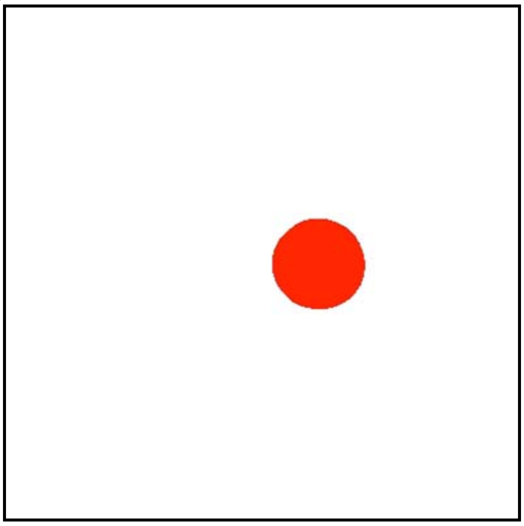


Fig. 5. Images resulting from the binarization threshold at the ratio of 178 pixels: a) binarization image of Fig. 2 a); b) binarization image of Fig. 3 f); c) cross-correlation function resulting from images presented on Fig 5 a) and 5 b)

It can store images of defects as binary functions, ie. zero - one sequence. Threshold should be fixed above which the function has a value of one, and below which the function is zero.

From the results shown in Table 2 shows that the nature of the correlation function was preserved and thus the conclusion that you can apply compression proposed above.

Tab. 2. Values of overlapping of functions (expression (13) for images resulting from the binarization with the threshold 178 pixels) for images showed on Fig. 5.

Image	Overlapping of functions (expression (13))
Fig 5 (a) – (Fig 2a and 3a)	55.19 %
Fig.5 (b) - (Fig. 2c and 3c)	77.01 %
Fig. 5 (c) - (Fig. 2e and 3d)	81,81 %
Fig. 5 (f) - (Fig. 2c and 3f)	14.76 %

5. SUMMARY

The method proposed by the authors for the assessment of head checking defects in railway rails is based on cross-correlation function. It is a new approach for laser scatterometry method. The real experiments conducted both for real and pattern HC defects confirmed its usefulness.

The advantage of the method based on cross-correlation function is its simplicity, it uses Fast Fourier Transform (FFT). It has been verified on pattern HC defects cut by laser on surface of the rail as well as real HC defects, whose images were presented in Fig.2 and 3.

Based on the experience gained during work on laser scatterometry, authors concluded that this method is highly sensitive. It results from high variability of images of real defects.. Although CCD camera does not ensure precise distribution intensity for the image, calculation results obtained in the experiment are satisfactory. Fig.4 and tab.1 present images and calculations for different image combination, respectively. Higher value of cross-correlation function corresponds to higher similarity between images. The range of this function varies from 16,6 to 84,93 %.

Next experiment was conducted for the same images, however before calculating cross-correlation function they were transformed to binary form using arbitrary chosen threshold. It allows for reduction of computer memory using to store outcomes. Fig. 5 and tab. 2 present images and calculations for different image combination, respectively. It should be noted that binarization process does not have an influence on the change in similarity between images. In this case the range of this function varies from 14,76 to 81,81 %. This result confirms the usefulness of this method.

In next stage of their work, authors are going to create procedures which allow for automatic assessment of HC defects. For this purpose authors will create database of images of pattern HC defects obtained using laser scatterometry method.

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