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REDUCING THE LEVEL OF INTERFERENCES IN THERMAL NON-DESTRUCTIVE TESTING CONSIDERING THE SPECIFIC THERMOPHYSICAL AND MORPHOLOGICAL CHARACTERISTICS OF THE OBJECTS

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ABSTRACT

Interferences, characteristic for non-destructive thermal testing which reduce the reliability of the obtained results are described. A technique for their reduction is suggested which consists of two interrelated stages. The first stage consists in calculating and analyzing the nature and level of the expected signal according to the developed thermophysical model against the background of the experimentally obtained interference level. According to the results of analysis of calculations using the thermophysical model for the selected samples, the most influential interference was the inhomogeneity of the emissivity of the sample surface. The second stage of processing the received data is devoted to reducing this interference. This stage consists in processing thermograms of temperature fields and includes morphological analysis of the surface condition, filtering and reducing characteristic interferences and interferences. It consists of four practical procedures: analysis of a visual image and obtaining a map of zones with a different emissivity of the sample surface, analysis of the thermogram with an assessment of the level of discreteness of the thermogram and the position of fiducial points on the image, smoothing the thermographic image and highlighting zones on the thermogram with different emissivity of the controlled object surface, after which the interference is filtered. Since the results of thermal testing are strongly influenced by the shape of an object, the possibilities and effectiveness of the suggested technique are illustrated on a cylindrical object. It has been experimentally confirmed that for the selected sample, it was possible to reduce the interference level to that of confident separation of a useful signal against the interference background.

KEYWORDS: thermal non-destructive testing, useful signal level, structural interference, thermophysical model, image processing, morphological analysis

INTRODUCTION

The active development of pipeline transport in the world began in the late 1960s, and now the length of main pipelines is hundreds of thousands of kilometers, including: gas pipelines, oil pipelines, water pipelines, heating and cooling systems. This gigantic infrastructure has been under load for tens of years, due to which it is prone to corrosion and wear. Monitoring the state of such systems by contact methods is a complex and expensive procedure. Therefore, for the mentioned objects, non-contact methods are more effective, which in most cases have no alternative. One of the promising methods of non-contact non-destructive testing is the thermal method (for objects that have their own thermal field). At present, there are a large number of algorithms for image quality enhancement, but they are ineffective for processing thermograms during non-destructive thermal testing. This is associated with the features of infrared radiation and the specifics of its registration. Therefore, it is not always possible to realize the potential of this method in practice due to the presence of significant interferences. The indicated drawback can be eliminated both at the stage of measurements as well as when processing the obtained results by taking into account the thermophysical characteristics and structural features of tested objects [1, 2].

INTERFERENCES IN THERMAL NON-DESTRUCTIVE TESTING

When realizing thermal testing (TT), the source of interferences and interferences is a testing object (TO), registration equipment, and the influence of the environment. Interferences can be added to the useful temperature signal T (additive interference $\tilde{A}$) or multiplied with it (multiplicative interference A) [1]:

$$u(x, y, \tau) = \tilde{M}T(x, y, \tau) + \tilde{A}. \quad (1)$$

From (1) it is seen that the signal $u \equiv T$ is registered only when $\tilde{M} \equiv 1$ and $\tilde{A} \equiv 0$. The best testing procedure is one in which the sensitivity of the method is limited by the radiation detector, i.e. $\tilde{M} \equiv 1$ and $\tilde{A} \to$ min. Interferences and interferences are also subject to this law, but the difference between them lies in the nature of their dependence: interference is a signal that has a random nature, and interference is a signal, whose magnitude is subject to the cause of its occurrence [3].

During active TT, the main source of external interference is the heater. During passive TT, external sources of thermal radiation can generate false signals that operator can interpret as signs of a defect. This problem is complicated by the fact that the radiation reflected from a testing object depends on the state of its surface and the registration angle.

To reduce interferences and increase the efficiency of thermal testing, a method based on the analysis of defect detection (TT procedure) and improved procedures of processing the obtained images of TO temperature fields was used. In addition to the surface condition, the shape of TO also plays an important role in thermal testing.

The specified aim is achieved using a theoretical-experimental approach, which combines the construction and analysis of a thermophysical model and the procedure of a computer processing of the results of testing an object of a complex shape. As an experimental sample, a fragment of the pressure pipeline, provided by specialists of the South Ukraine NPP, was used.

SELECTION OF A THERMOPHYSICAL MODEL

The proposed technique consists of two interrelated stages. The first stage consists in the calculation and analysis of the nature and level of the expected signal according to the developed thermophysical model against the background of the experimentally obtained level of interferences. According to the results of the analysis of calculations based on the thermophysical model for the selected samples, the procedure of the further computer processing of the obtained data is selected [4, 5]. The second stage consists in the processing of thermograms of temperature fields and includes a morphological analysis of the state of the surface, filtering and reduction of characteristic interferences and interferences. The main condition for an adequate description of the testing process is the selection of both physical and mathematical models, which most fully reflect the features of heat transfer in a defect and a product, and also allow analyzing the model of a tested object, features of the process and calculating quantitative parameters with the required accuracy.

As a model of TO, a thermophysical model of a cylindrical shape with a local defect of a type of wall thinning, shown in Figure 1, was selected. The testing object is represented as a cylinder with inhomogeneity (defect). The defect in the form of the wall thinning is modeled by a groove inside TO with the depth h_d and the size l_d.

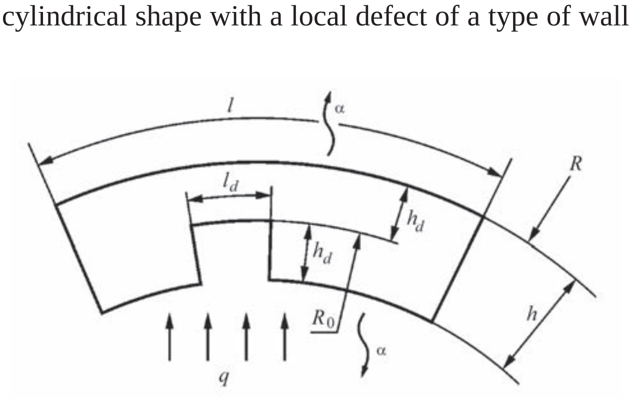

Figure 1. Testing object with a defect of the type of thinning of the pipeline wall

The following equation corresponds to the selected model:

$$\operatorname{div}(\lambda(T)\nabla T(\vec{r},t)) + Q(\vec{r},t) = c\rho \frac{\partial T(\vec{r},t)}{\partial t}, \qquad (2)$$

where $T(\vec{r} < t)$ is the temperature of the testing object, which depends on the coordinates of point M and time t; $\lambda(T)$ is the coefficient of thermal conductivity, W/(m·K) (in general case, it may depend on the temperature T); $Q(\vec{r}\ , t)$ is the function of inner heat sources, W/m^2; c is a specific heat capacity, J/(kg·K); ρ is the density of the substance, kg/m^3. If R_1 is the inner radius of TO; R is the outer radius of TO, then $\lambda(T)$ for $r < R_1$ equals to $\lambda_1(T)$, for $R_1 < r < R - \lambda_2(T)$, for $r > R - \lambda_3(T)$.

For a real process of thermal testing (thermal flaw detection), the equation (2) can be simplified taking into account the following factors: inner sources are absent and the coefficient of thermal conductivity does not depend on the temperature, because heating of TO does not exceed 100 °C. Taking this into account, we obtain [3]:

$$\left(\lambda(T)\frac{\partial^2 T}{\partial x^2} + \frac{\partial \lambda(\vec{r})}{\partial x}\frac{\partial T}{\partial x}\right) + \left(\lambda(T)\frac{\partial^2 T}{\partial y^2} + \frac{\partial \lambda(\vec{r})}{\partial y}\frac{\partial T}{\partial y}\right) + \\ + \left(\lambda(T)\frac{\partial^2 T}{\partial z^2} + \frac{\partial \lambda(\vec{r})}{\partial z}\frac{\partial T}{\partial z}\right) = c\rho\frac{\partial T(\vec{r},t)}{\partial t}. \qquad (3)$$

The equation (3) is a homogeneous linear differential equation of the second order of the parabolic type as far as $\lambda \geq 0$. Namely this equation adequately describes the selected thermophysical model (Figure 1) provided that it is solved under correctly selected boundary conditions corresponding to the real procedure of thermal testing, i.e. at the boundary conditions of the 2nd and 3rd kind on the outer surfaces of TO [6]:

$$\begin{cases} r = R_0 \\ \lambda(\vec{r},T)\dfrac{\partial T(\vec{r},t)}{\partial n}\Bigg|_S = \alpha\left(T(\vec{r},t)\Big|_S - T_{\text{invironm}}\right) - q(\vec{r},t) \end{cases}; \qquad (4)$$

$$\begin{cases} r = R \\ -\lambda(\vec{r},T)\dfrac{\partial T(\vec{r},t)}{\partial n}\Bigg|_S = -\alpha\left(T(\vec{r},t)\Big|_S - T_{\text{invironm}}\right) \end{cases}, \qquad (5)$$

where $q(\vec{r}\ , t)$ is the heat flow density, W/m^2; α is the heat transfer coefficient, W/(m^2·K); R_0 is the radius of the surface on which defect is located, m; h is the thickness of TO, m.

The ratios (4) and (5) reflect the real conditions of conducting an active TT, i.e. heating of TO by an external heating source and the presence of heat exchange with the environment. The mathematical model of the process is based on the solution of the differential equation of nonstationary thermal conductivity (2) recorded for the cylindrical coordinate system [7, 8].

The thermogram of the experimental sample with an interference caused by the inhomogeneity of the emissivity of the sample surface is shown in Figure 2. Based on the analysis of the results of calculations carried out according to the thermophysical model and data obtained from the thermograms of visual images of the testing object, the following results were obtained:

- the level of the expected signal is ~2–3 °C;
- the largest contribution to the level of interference is made by a multiplicative interference caused by the inhomogeneity of the emissivity of the sample;
- the level of a dominant interference is about ~4.3 °C.

The level of the useful signal and interference are close by an order of magnitude (according to Figure 2). Therefore, the thermogram needs further computer processing to reduce the dominant interference.

PROCESSING OF THERMAL TESTING RESULTS

The actual levels of interferences and interferences on experimental samples, for which thermophysical models were developed, are shown in Figure 3. As is seen, the level of the interference signal does not allow a reliable detection of defects. It is also clear that these interferences cannot be removed by the methods of graphical image processing, but additional information can be applied, obtained earlier during modeling.

The thermogram analysis (Figure 2) showed that the greatest contribution to the level of interferences is caused by the inhomogeneity of the emissivity and is associated with the state of the surface and the change in the registration angle of radiation, which is typical of cylindrical objects with a small radius.

The essence of the proposed method of processing thermogram of TO with a complex geometry consists in compensating for interferences in the areas of their presence. The proposed method makes it possible to highlight such zones by using the obtained a priori information from a visible image in the form of a map of zones with a different emissivity and comparing it with the thermogram.

To automate the process of comparing the map of zones with a different emissivity and the thermogram, an algorithm was proposed, which consists of the following procedures:

- visual image analysis (receiving a map of zones with different emissivity of the sample surface);

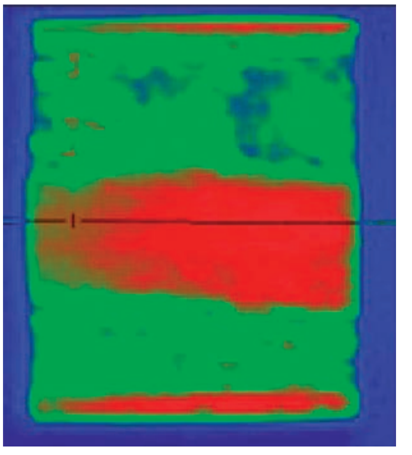

Figure 2. Thermogram of the pipeline fragment with a defect and probable interferences

- thermogram analysis (assessment of the level of discreteness of the thermogram and the position of fiducial points);
- preliminary image processing (smoothing of a thermographic image, because, as a rule, it is more discrete than visible);
- allocation of zones with different emissivity of TO surface on the thermogram (takes place during overlay of the map of zones on the thermogram by combining fiducial points).

In image processing and recognition of the zones of interest, a limited set of methods for preliminary image processing is used [9]. This is associated with the fact that modern systems for TO registration are designed for operator control, which allows maintaining the characteristics of obtained images in a narrow range, corresponding to the optimal testing mode [4].

Then, to highlight the zone of interest on the thermogram, a visible image is normalized using two fiducial points selected on the thermogram and on a visible image. The normalization is necessary to obtain a more accurate contour of the zone of interest on the thermogram. After the stage of image preparation, fiducial points are allocated on a visible image inside the contour of an object. This stage is also carried out on the thermogram. After that, the contour is transferred from a visible image to the thermogram. To do that, it is necessary to perform the following steps:

- preparation of a visible image, which includes filtering, allocation of contours, normalization (scaling and rotation) and segmentation (allocation of an object by fiducial points). The described stages at a correct selection of methods allow obtaining a contour in a visible image for its further overlay on the thermogram;
- carrying out analysis of the thermogram, which includes normalization and allocation of fiducial points and the zone of interest on the thermogram and a visible image. Highlighting the zone of inter-

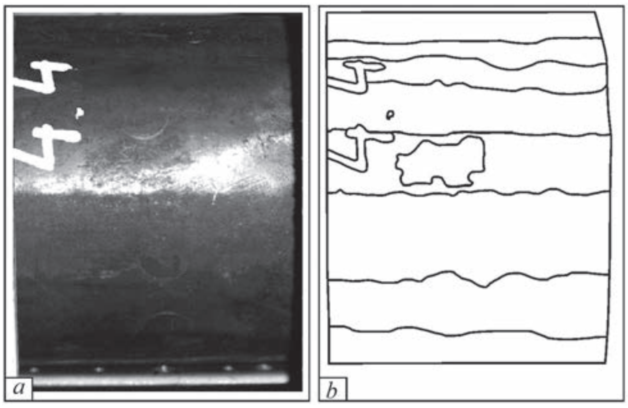

Figure 3. Visible image of the pipe fragment (*a*) and the result of processing image by the Roberts operator after filtering (*b*)

est consists of two stages: transfer of the contours of an allocated object obtained in a visible image to the thermogram and detection of zones with the average emissivity on the studied surface of the samples [10].

With a help of the obtained contour of the zone it is possible to analyze it by temperature values [1, 4].

There are many methods of a visible image filtering: convolution, combined filtering with a differentiated smoothing of areas with different information value, median method, linear and nonlinear filtering, SUSAN method [4], from which in the carried out experimental studies the methods of median filtering and SUSAN were used.

Due to such a procedure, texture interferences were suppressed, which simplified the further processing. Visual analysis did not reveal significant changes, but the need in such a filtering is a very important stage for the further processing.

The next stage in preparing a visible image is the contours allocation. In order to do that, on a visible image, the method of active contours, Roberts operator, Laplace operator and the difference method were selected. In the developed software product, the Roberts method and the difference method are presented. Before processing of an image by the mentioned methods, it is necessary to carry out a preliminary filtering by the SUSAN method, because for the correct operation of the Roberts operator, a continuous function of intensity is required, and the basic image has a discrete function [4]. The result of using the Roberts operator is shown in Figure 3.

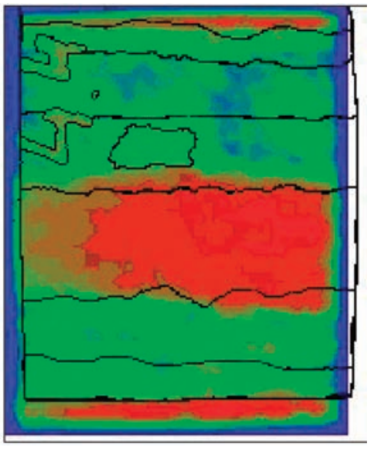

Figure 4. Overlay of a filtered visible image on a thermographic one

Over the two-dimensional function, obtained as a result of processing, a smoothing filtering was carried out to reduce the discretization of zones and to obtain a continuous contour of the zone regardless of what method was used to allocate the contour. At this stage of the algorithm, the overlay function was realized. It allows combining a filtered image with the thermogram of an object. The result of this function is presented in Figure 4.

For each zone, the correction factor [1] was set, which compensated for the inhomogeneity of the emissivity and the registration angle in the specified area. Thus, interferences mentioned earlier were filtered and the initial temperature field was restored (Figure 5).

The obtained results show that the temperature field (Figure 5, *b*) increases from left to right, which corresponds to the reduction in the thickness of the sample wall (Figure 5, *c*). As is seen from the abovementioned thermograms, the level of a structural interference, caused by the inhomogeneity of the

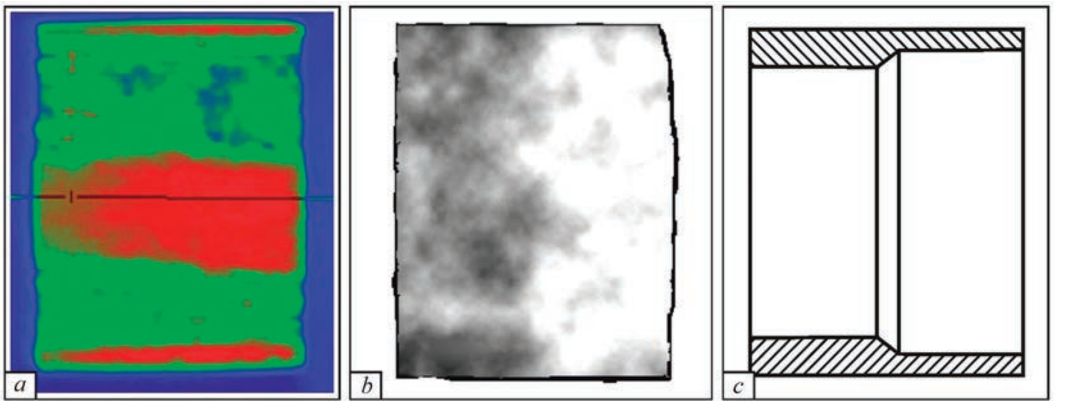

Figure 5. Results of the experiment: thermogram of the steam line fragment (*a*), restored temperature field of TO (*b*), cross-section of the sample (*c*)

emissivity of the surface and the angle of registration of the sample, decreased from 4.3 to 0.7 °C, i.e. by 3.6 °C. The level of non-dominant interferences and interferences amounts to 1.1 °C, which does not interfere with the separation of a useful signal on their background. Thus, the proposed technique allowed revealing the inner structure of the sample — an area with a different wall thickness and the boundary between them.

CONCLUSIONS

The method of processing the results of a thermal testing is proposed, which allows taking into account the features of infrared radiation and specifics of its registration. The method allows reducing the level of structural interferences, which is based on the analysis of a thermophysical model and morphological features of visible and temperature images.

The carried out theoretical and experimental studies showed the effectiveness of a new approach to the analysis of thermal images in a thermal non-destructive testing.

The thermophysical model of testing an object of a cylindrical shape was developed, which takes into account the peculiarities of heat transfer in a defect and on the basis of which it is possible to calculate and analyze the nature and level of the expected signal on the background of experimentally obtained level of interference.

Using the system of correction factors for different zones on the surface of a testing object allows getting closer to solving a complex problem for the thermal method — testing objects of a complex shape and objects that have regular structural heterogeneities.

The described algorithm allows processing image and compensating interference when it cannot be minimized by optimizing the active testing mode [8].

The carried out experiment confirmed the validity and correctness of the theoretical provisions and allowed determining the inner structure of a studied object (different wall thickness) and reducing the level of structural interferences by 3.6 °C (from 4.3 to 0.7 °C).

The studies show that processing of experimental data, carried out taking into account the peculiarities of thermophysical and structural characteristics of testing objects provides a significant positive result and is an important step to automation of procedures of a thermal non-destructive testing on its path of introduction into the mass production.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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