STATISTICAL APPROACH IN THERMAL TESTING OF THE MACHINES AND MECHANISMS TECHNICAL CONDITION

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Abstract: Approach for defects detection in units of industrial equipment of the same type is developed. This approach is based on the statistical processing of thermographic testing results. Information attributes and decision rules for such units rejecting are defined which take into account the probability of errors of type I and type II. The entity of this approach is that integral conformity criterion for the verification object and virtual template is calculated. When calculating this criterion from the obtained thermal images its histograms are used and their differences by shape, by height as well as by position on the temperature axis are taken into account. The approach has been tested on the gas-compressor units particularly on the gas-engine compressors.

Keywords: thermography, diagnostics, hidden defect, gas-engine compressor, informative attributes, reference infrared image.

1. Introduction

Technical diagnostics and non-destructive testing as a part of the quality assurance system play an increasing role in the global economy, especially in those sectors of industry that require increased reliability of technical systems, machines and equipment (aerospace technology, power engineering, pipelines and railway transport).

Thermography is a promising and rapidly developing concept of technical diagnostics. Thermography is based on measuring the excess temperature field that appears on the verification object surface due to its functioning. The temperature field is recorded with the help of a special device – thermal imager – in the form of infrared images (thermograms). Their analysis gives the possibility to detect the local anomalies of temperature field on the surface of verification object (VO).

In order to relate these temperature anomalies to the VO quality factors, the obtained thermograms must be processed. It is usually done with the standard software built into the thermal imager. Therewith the processing task is to improve the visual informativeness of these infrared images, using different palettes, filtering, selection of a certain temperature range, etc.

However, such methods of thermograms processing do not enable solving the main task of nondestructive testing, namely, to make a conclusion about VO compliance with the required quality level, i.e. to reveal hidden defects.

The purpose of this study is to develop an approach for processing the results of thermographic testing based on the selection of relevant informative attributes, development of a quality standard, and definition a decision rule for VO classification by the results of its comparison with the standard.

2. Verification object details

This task was considered on an example of a specific object namely gas engine compressor of 10GKN type used at a number of compressor stations in Ukraine. This VO is of some interest because some of units in 10GKN equipment are not equipped with technical control means. There are also a range of defects (leakiness of gas joints, violation of coolant circulation) which can be revealed in an expeditious manner only with thermographic testing.

An important feature of this VO is the presence of the same type units with very close temperature operating modes. Therefore, it is possible to identify a supposedly defective unit by comparing their infrared images [1]. The following groups of units are distinguished for the specified VO, which are represented with infrared images shown on Fig. 1–3.

3. Interfering factors

The results of the studies showed that the following interfering factors exert a great influence over testing: positioning inaccuracy of the thermal imager during the survey, the surface inhomogeneity by the emissivity, exposure from external sources occurrence [1].

Therefore, it was suggested in these studies to compare not the temperature fields, but their histograms [2], which are more resistant to the interference effects.

The infrared image of VO from a mathematical

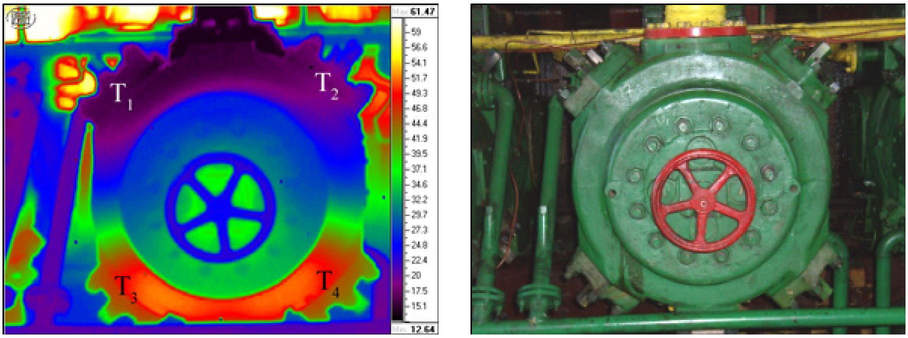

Fig. 1. Compressor Cylinder (5 units per plant)

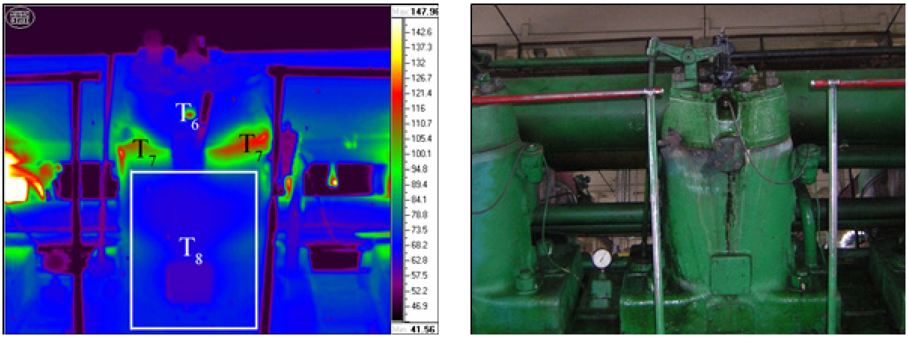

Fig. 2. Power Cylinder (10 units per plant)

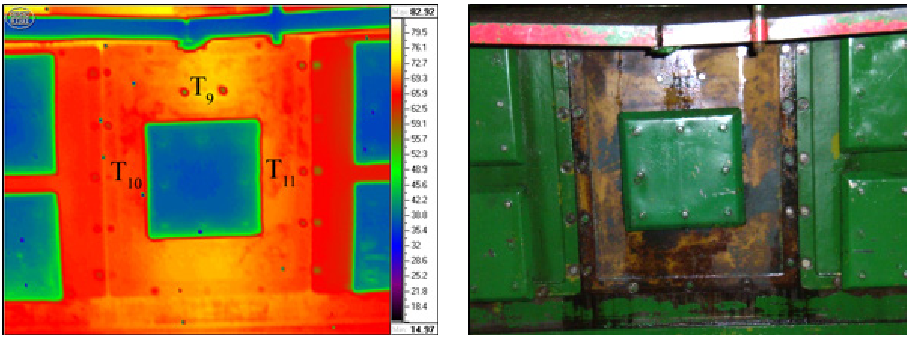

Fig. 3. Housing Assembly fragment in the Connecting-Rod Gear area (5 units per plant)

standpoint is a matrix of temperature values for every pixel of the image. This matrix can be considered as a sample and to be analyzed with statistical methods. The histogram (frequency polygon) or distribution (fitting curve) can be built up for each range of interest of the infrared image. On the histogram or on its envelope (which is built after the manner of locally weighted averages) the temperature values are plotted on the abscissa, and normalized values of pixels number are plotted on the ordinate.

As an example, histograms of temperature fields in the Fig. 4 describe the forward pairs of compressor cylinders pressure valves.

From Fig. 4 it can be seen that the histograms

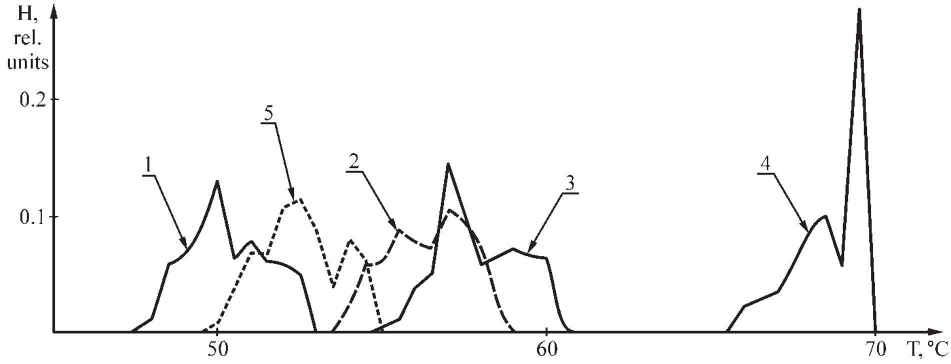

Fig.4. Histograms envelopes for a group (5 units) of pressure valves that belong to one gas engine compressor plant

differ from each other in the following attributes: form, arrangement on the temperature axis and background level (peak height). The most dramatic difference is registered for the valve No 4.

4. Informative attributes

The following informative attributes are proposed to introduce for quantitative description of differences between histograms.

The conjunction known from the image analysis theory [3] may be used as the attribute which accounts for differences between histograms by their form:

$$D1 = \sum_{i=1}^{N} \left| H(i) - H_{ref}(i) \right|, \quad (1)$$

where: $H(i)$ is the i-th histogram element of the infrared image being analyzed, $H_{ref}(i)$ is the i-th histogram element of the reference infrared image, N is the number of elements for infrared image decomposition.

In our case it is more preferred to use the modification of this attribute, i.e. the distance between the histograms of analyzed and he reference infrared images. It can be calculated by element-wise comparison of histograms together with neighboring elements [4]. This reduces the effect of weaker distinctions. It is therefore necessary to calculate not one but three differences for each histogram element:

$$D1a = \sum_{i=1}^{N} \min\left(\left| H(i) - H_{ref}(i-1) \right|, \left| H(i) - H_{ref}(i) \right|, \left| H(i) - H_{ref}(i+1) \right| \right) \quad (2)$$

The information attribute taking into account the difference between histograms and the background content may be given as the ratio [5]

$$D2 = \left| \Pr(H) - \Pr(H_{ref}) \right|, \quad (3)$$

where: $\Pr(H), \Pr(H_{ref})$ are the maximum peak values of the obtained histogram for the analyzed and reference infrared images.

The third attribute taking into account the histogram arrangement on the temperature axis may be Cramer–Welch criterion [6]. The main advantage of it is that it takes into account not only the average value of the temperature of the range of interest selected (or of the entire image), but also the temperature contrast of this range (the variance of temperature values). This attribute is also insensitive to operator mistakes when choosing a range of interest. Cramer–Welch criterion is estimated by formula:

$$D3 = \frac{\sqrt{m}\left(\mu(X) - \mu(X_{ref})\right)}{\sqrt{n\sigma^2(X) + m\sigma^2(X_{ref})}} \quad (4)$$

where: $\mu(X), \mu(X_{ref})$ are the theoretical averages for the analyzed and reference infrared images, $\sigma(X), \sigma(X_{ref})$ are the mean–square deviations of the analyzed and reference infrared images, $n \times m$ is the image size.

When performing the examination for the proposed attributes (2) – (4) use it is necessary to have a reference (the infrared image of a known defect-free unit). In practice, allocation of such a reference in a real VO is very problematic. It leads to the conclusion that a virtual reference is necessary.

Such a reference (reference infrared image) was obtained by averaging the infrared images of the same type of units [7]. On this principle the infrared images were obtained for each type of compressor units.

Taking into account that the statistical sample obtained from 5 to 10 identical units is considered as a small sample than the nondeterministic run outs were excluded when the reference was built.

5. Defectiveness criteria

To formulate the defectiveness criteria for each of the mentioned information attributes ($D1a$, $D2$ and $D3$), an analysis of their distribution was performed. It turned out to be close to the normal law, and this gave the possibility to use the "two sigma" rule for defectiveness criterion formulation [8]:

$$\begin{aligned} (D1a)_i &\geq \mu_{D1a} + 2\sigma_{D1a}, \\ (D2)_i &\geq \mu_{D2} + 2\sigma_{D2}, \\ (D3)_i &\geq \mu_{D3} + 2\sigma_{D3}, \end{aligned} \tag{5}$$

where $(D1a)_i$, $(D2)_i$, $(D3)_i$ are the $D1a$, $D2$ and $D3$ attributes respectively for *i*–th unit under control; μ_{D1a}, μ_{D2}, μ_{D3} are their theoretical averages by all the units under control totality; σ_{D1a}, σ_{D2}, σ_{D3} are the mean-square deviations of the $D1a$, $D2$ and $D3$ respectively.

Such defectiveness criteria approbation on the infrared images of the 10GKN type gas-engine compressor units showed significant discrepancies in the results of the sorting for every single one of them. For example, by the $D1a$ criterion 4 suction valves were rejected but by the $D3$ criterion two of them passed that sorting.

Therefore if we use only the one of the considered criteria it might cause significant errors of the second kind when sorting. For this purpose it is more effectually to use the integral conformity criterion as a criterion of defectiveness. This criterion combines the assessment by all the three considered attributes ($D1a$, $D2$, $D3$) which are almost uncorrelated to each other (per paired correlation coefficients calculation $k_{D1a,D2} = 0.4$; $k_{D2,D3} = 0$; $k_{D1a,D3} = 0.1$).

The proposed integral conformity criterion I is given by:

$$I = (D1a*)^2 + (D2*)^2 + (D3*)^2, \tag{6}$$

where: $D1a*$, $D2*$, $D3*$ are the standardized values for $D1a$, $D2$, $D3$ criteria. According to [8] the standardized values are defined with the following relations:

$$\begin{aligned} D1a* &= \frac{D1a - \mu_{D1a}}{\sigma_{D1a}}, \\ D2* &= \frac{D2 - \mu_{D2}}{\sigma_{D2}}, \\ D3* &= \frac{D3 - \mu_{D3}}{\sigma_{D3}}. \end{aligned} \tag{7}$$

Since the I (6) criterion distribution according to [8] is a chi-square distribution with three degrees of freedom then to determine its critical value for a given value of confidence (error of the first kind) the reference tables of this distribution can be used. In particular, for type I error level $\alpha = 0.05$ per [9] the critical value is $I_{cr} = 7.81$.

Thus taking (6) and (7) into account the decision rule for gas-engine compressor units sorting is given by (8).

The calculations performed by (6–8) indicated 6 defective units out of 104 considered, in other words the maximum type I error is $\alpha = 0.06$.

Considering that there are no any actual data on the VO units defectiveness as it will be necessary to perform a complete disassembly of the compressors for this purpose then it is not possible to estimate the type II error (β) from the obtained data. However it is known [10] that there is a particular relation between α and β: the higher α, the lower β value and vice versa.

$$I = \left(\frac{D1a - \mu_{D1a}}{\sigma_{D1a}} \right)^2 + \left(\frac{D2 - \mu_{D2}}{\sigma_{D2}} \right)^2 + \left(\frac{D3 - \mu_{D3}}{\sigma_{D3}} \right)^2 > 7.81 \tag{8}$$