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*Original article*

## Self-reference Lock-in Thermography for Detecting Defects in Metal Bridge Spans

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**Abstract**

***Introduction.*** Incipient fatigue damage in the metal superstructures of bridges creates certain threats to the safety of operation. Various methods of non-destructive testing are used for their timely detection and diagnosis. A modern and popular on-the-day solution is the method of infrared (IR) thermography. Due to the specifics of the operation of IR cameras, additional processing of recordings received from these cameras is required to obtain an accurate result. This work aims at presenting a method for processing thermofilms and describing the possibilities of its application under real conditions.

***Materials and Methods.*** A method for processing thermographic films was described. It provided detecting temperature anomalies using only information from the camera. The results of its application on the elements of existing metal bridge spans are presented.

***Results.*** It is shown that there are temperature anomalies for existing defects. This means that the defects continue to develop, which was confirmed by subsequent observations of their condition. In addition, a case of temperature anomaly in the defect-free external region was identified. This might be a sign of an incipient defect that could not be diagnosed by other methods. If the presence of this defect is confirmed during repeated examinations, it will be possible to diagnose hidden defects that have not yet come to the surface, and/or detect potentially collapsing places.

***Discussion and Conclusions.*** The IR thermography performance as a method of non-contact non-destructive testing is shown, as well as its operability on real objects under random load.

**Keywords:** IR thermography, nondestructive testing, fatigue cracks, metal bridges, structural defects, IR camera.

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**Introduction.** Fatigue cracks in the metal structures of bridges, formed under the influence of transport loads, wind loads, etc., are a serious challenge. Although these cracks in themselves only affect the durability of the structure, under certain conditions, they can give rise to the development of brittle cracks, which directly affects the safe use of structures [1].

One of the modern methods of non-destructive testing, which is gaining popularity, is IR thermography [2–12]. The method principle is based on the fact that any body that is subjected to mechanical action releases an amount of heat proportional to the intensity of the action. Therefore, when examining a section of the structure containing defects, you can immediately get information about the distribution of stresses in this section. A different temperature distribution will be an indicator of ongoing fatigue damage [13, 14].

The major challenge when working with IR cameras (thermal imagers) is to obtain results with acceptable accuracy. Due to the structural features of the detectors, the highest accuracy is achieved when using cold sensor cameras. However, the high cost of such devices is a serious obstacle to their use. The introduction of cameras using uncooled arrays of microbolometers improved the situation, as these cameras turned out to be noticeably cheaper. The disadvantage of such thermal imagers is the lower accuracy compared to cameras with cooled matrices. Therefore, to get stable results, additional processing of the obtained thermograms is required.

This work aimed at evaluating the effectiveness of self-reference lock-in thermography using a signal obtained directly from thermal imaging[1].

**Materials and Methods.** The IR thermography method is based on the analysis of the temperature distribution in the material. When tensile or compressive stresses are applied to a material, its temperature changes in proportion to the magnitude of these stresses in accordance with the following formula[2]:

$$\Delta T = -\frac{\alpha}{\rho \cdot C_p} T \cdot \Delta\sigma, \quad (1)$$

where α — thermal-expansion coefficient; ρ — matter density; $C_p$ — specific heat capacity at constant pressure; $T$ — absolute temperature, K; Δσ — change in principal stresses, MPa.

When adiabatic conditions are maintained, as well as when elastic deformations develop only, the coupling (1) is linear and reversible, in which a change in temperature follows a change in stress. As soon as damage begins to form in the material, it ceases to be elastic and develops plastic deformations. The energy of a system subject to such deformations is intensively converted into thermal energy, thus making the main contribution to the thermal effect. Hence, the thermal picture becomes a reflection of the internal state of the material (the degree of destruction) and, consequently, an indicator of the stress level.

The relative amplitude of an IR signal can be determined using the least squares method[3]. Let us assume that load F, whose impact in a certain area can be measured and denoted as $f(t)$, acts on the structure. We will consider this signal as the reference one. Suppose there is also an IR video recording of this construction in the same time interval, which can be presented as a sequence of frames (a frame is a matrix of values $M \times K$ in size) in time, and we denote values ($i$, $j$) of the element of this matrix (pixel) at time $t$ where $1 \le i \le M$, $1 \le j \le K$, as $y_{ij}(t)$. We denote the approximation function for this element as:

$$Y_{ij}(t) = a_{ij} + b_{ij} f(t), \quad (2)$$

where $a_{ij}$ — bias; $b_{ij}$ — coefficient of influence of the reference signal $f$.



[1]Sakagami T, Nishimura T, Kubo S, et al. Development of a Self-reference Lock-in Thermography for Remote Nondestructive Testing of Fatigue Crack (1st Report, Fundamental Study Using Welded Steel Samples). Transactions of the Japan Society of Mechanical Engineers. Series A. 2006;72:1860-1867. https://doi.org/10.1299/kikaia.72.1860

[2]Thomson W. (Lord Kelvin). On the dynamical theory of heat. Trans. R. Soc. Edinburgh. 1853;20:261-283.

[3] Lesniak JR, Boyce BR, Howenwater G. Thermoelastic Measurement Under Random Loading. In: Proc. SEM Spring Conf., 1998. P. 504-507.

Using function (2), we approximate signals $y_{ij}(t)$ from the thermal imaging film. Let us show how to find these coefficients for some $y_{ij}(t)$, the reasoning for the rest will be similar. We will minimize the deviation of our approximation from the signal received from the camera:

$$\Delta^2 = \sum_{n=1}^{N} \left( y_{ij}(n) - Y_{ij}(n) \right)^2 \to \min, \tag{3}$$

where $N$ — number of frames in the recording; $n$ — frame number corresponding to the time. From here, $b_{ij}$ can be found as follows:

$$b_{ij} = \frac{\begin{vmatrix} N & \sum_{n=1}^{N} y_{ij}(n) \\ \sum_{n=1}^{N} f(n) & \sum_{n=1}^{N} y_{ij}(n) f(n) \end{vmatrix}}{\begin{vmatrix} N & \sum_{n=1}^{N} f(n) \\ \sum_{n=1}^{N} f(n) & \sum_{n=1}^{N} f^2(n) \end{vmatrix}} = \frac{N\sum_{n=1}^{N} y_{ij}(n) f(n) - \sum_{n=1}^{N} f(n) \sum_{n=1}^{N} y_{ij}(n)}{N\sum_{n=1}^{N} f^2(n) - \left( \sum_{n=1}^{N} f(n) \right)^2}. \tag{4}$$

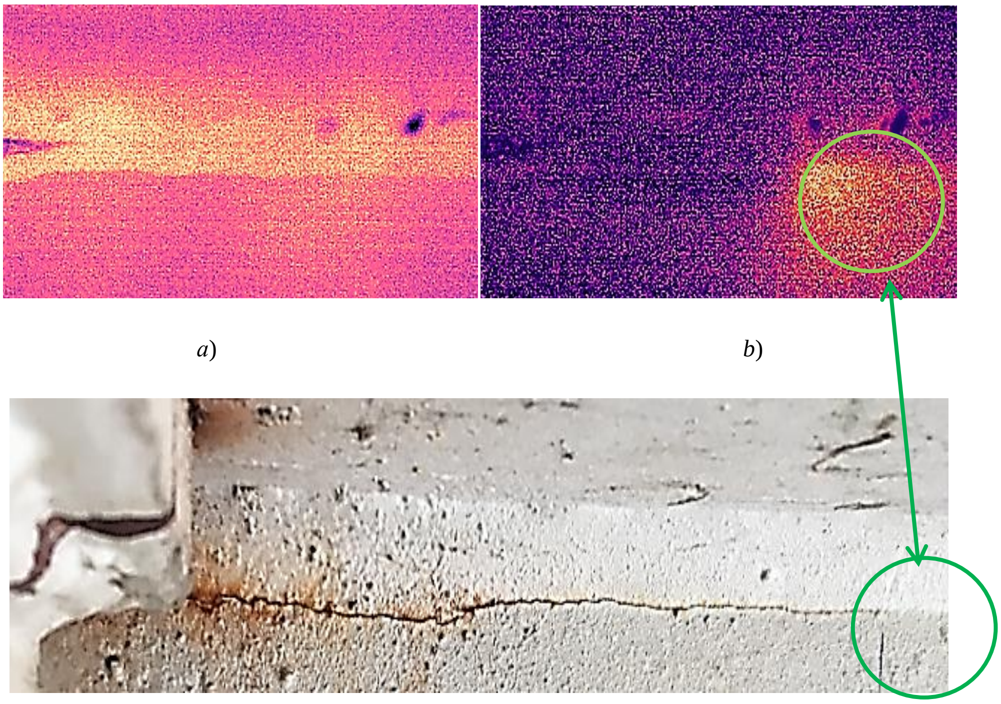
Through repeating (3) and (4) for all ($i$, $j$), we get matrix $B = \{b_{ij}\}$ of the same size as the original shooting frame. Thus, we obtain an approximation of each signal $y_{ij}(t)$ of the IR survey in time by means of reference signal $f(t)$. The values of matrix $B$ show the relative intensity of the temperature change in a certain area compared to the intensity of the reference signal change. Reference signal $f(t)$ may not necessarily be received from a third-party system, e.g., from a tensometer. The described approach, called self-reference lock-in thermography, can also be applied with a reference signal obtained from the same IR recording[4] [15, 16].

**Research Results.** The proposed algorithm was implemented in the form of Python scripts. With the help of these scripts, thermographic films recorded on the metal spans of existing automobile bridges, in whose structures fatigue cracks had been previously diagnosed, were processed. The performance of the algorithm was verified on the bench tests simulating the behavior of real structures with known information about the defect. The survey was carried out using an infrared camera with uncooled microbolometer Fluke Ti 400 having a thermal sensitivity of less than 0.05°C and a shooting frequency of 9 Hz. The recordings were made at the time of the impact of the automobile load on the bridge. As reference signals for each record, a defect-free zone of 15×15 pixels was used from the same structural element near the existing and/or proposed destruction zone. Processing results were visually presented in the form of images obtained by means of matrix $B$ values. Each value of the matrix corresponded to one pixel in the image, the number was converted to color using the palette function defined in the matplotlib package.

Figure 1 shows a fragment of a superstructure steel beam. A crack was found at the junction of the horizontal sheet with the wall (Fig. 1 *c*). Figure 1*a* shows one of the frames of IR film of this crack. Figure 1 *b* presents the result of processing, which clearly shows a spot, indicating heating occurring in the designated area. This zone corresponds to the area around the crack tip, which indicates the continued development of the defect. This was also confirmed by repeated surveys, which established an increase in cracks of more than 30% over 4 years.



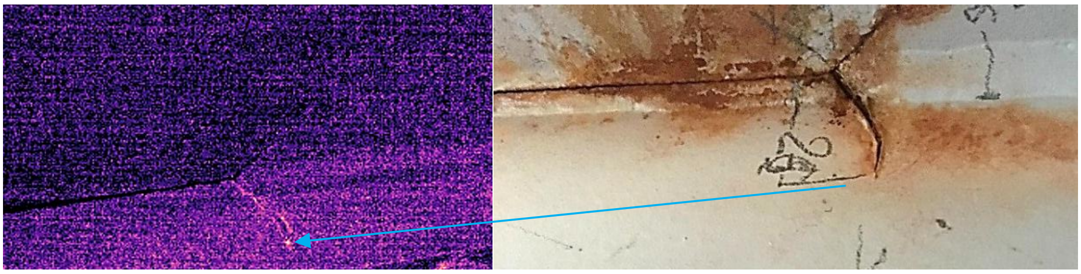
[4] Galietti U, Modugno D, Spagnolo L. A novel signal processing method for TSA applications Measurement Science and Technology. 2005;16:2251. http://dx.doi.org/10.1088/0957-0233/16/11/017



*a*) *b*) *c*)

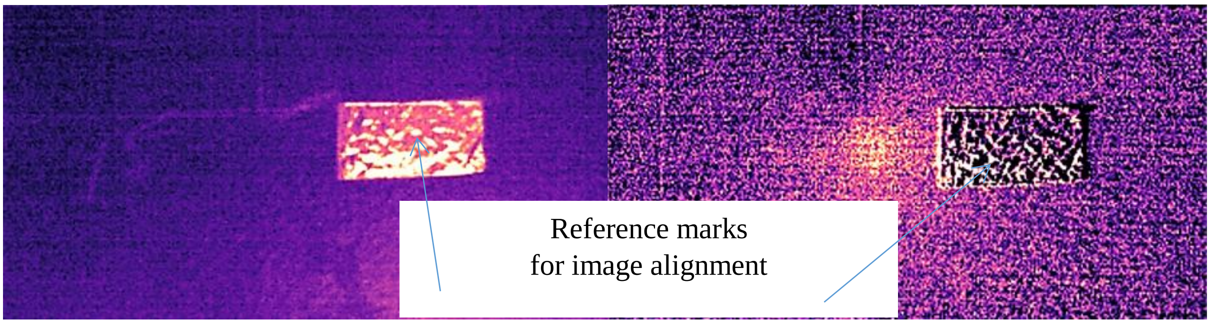
Fig. 1. Infrared results:
*a* — film frame; *b* — image built on the values of matrix *B*; *c* — photograph of the crack

Figures 2 and 3 show cracks that originated in the weld, then bifurcated and went into the stiffener and decking. The survey was carried out under the bridge tests. Strain gauges were installed in the same places to monitor the stresses, the results of which confirmed the development of these cracks.



*a*) *b*)

Fig. 2. Diagnosed fatigue crack:
*a* — image built on the values of matrix *B*; *b* — photograph




*a*) *b*)


*c*)

Fig. 3. Diagnosed fatigue crack:
*a* — film frame; *b* — image built on the values of matrix *B*; *c* — photograph of a crack

Figure 4 shows the combined readings of tensometers and temperature for the same section of the structure. Temperature indicators were obtained through averaging in the survey area and subsequent smoothing over time. The strain gauge data were also smoothed. As can be seen, the temperature change completely repeats the voltage change up to the sensitivity of the device.

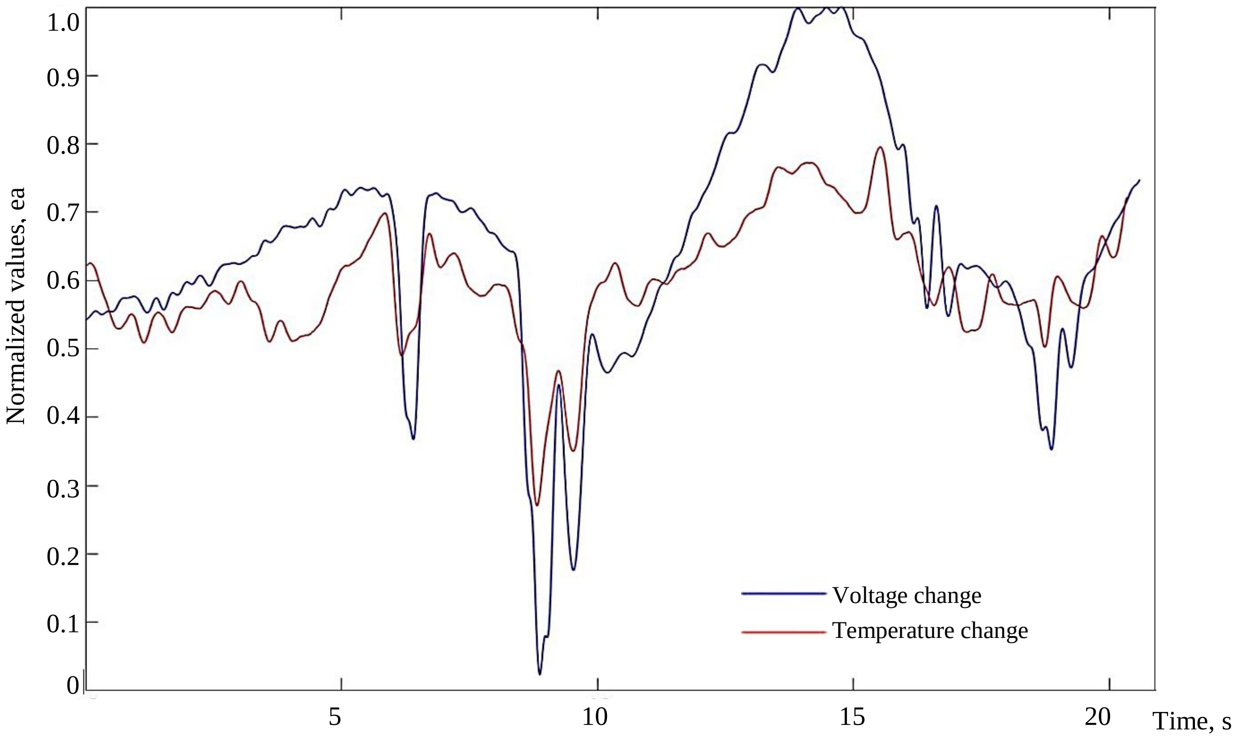
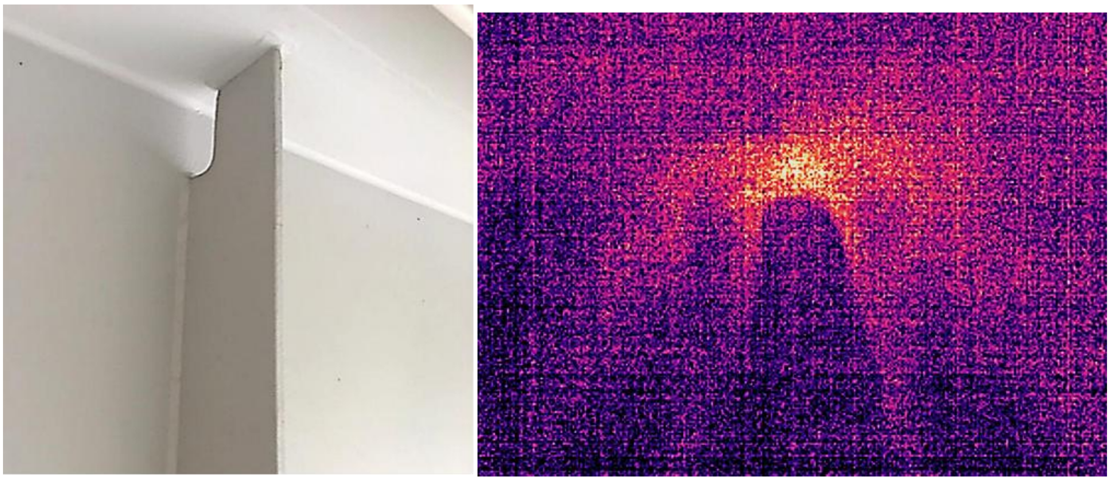



Fig. 4. Voltage changes graphs combined with temperature changes (temperature changes are taken with the opposite sign). Values along the y-axis are normalized with respect to unity

Figure 5 shows a structural element that had no visible damage, which was also not unambiguously determined by other methods. However, as a result of processing the thermogram package, it was found that there was a thermal anomaly at the junction of two elements. This indicates that the material was probably self-heating at this point, and a defect was emerging under the surface, which would soon have to come to the surface. Thus, this section of the structure requires additional attention under future surveys.



*a*) *b*)

Fig. 5. Infrared results: *a* — weld seam without visible fatigue damage; *b* — image of the weld toe, built from the values of matrix *B*

**Discussion and Conclusions.** The work carried out on the superstructures showed the effectiveness of self-reference lock-in thermography as a method of contactless diagnostics. The method performance on real objects under random load was shown. There was a correspondence of the stress change in the structure with the change in the recorded temperature. We carried out the diagnostics of some known defects, on which the continued development of damage was noted, which was subsequently confirmed by repeated examinations of these structural elements. In addition, a case of self-heating in an externally defect-free zone was identified, which indicated a probable process of the origin of the defect, which at the time of shooting could not be unambiguously diagnosed by other methods. This proves that this site requires additional monitoring. If a defect is detected at this site in the course of subsequent observations, we can talk about the possibility of using IR thermography to identify hidden defects and predict their appearance.

**References**

1. Solovyev LY, Solovyev AL. New technologies in bridge inspection. Proceedings of Siberian Transport University. 2020;54:14-20.

2. Vavilov V, Burleigh D. Infrared Thermography and Thermal Nondestructive Testing. Cham : Springer, 2020. 598 p.

3. Pitarresi G, Cappello R, Catalanotti G. Quantitative thermoelastic stress analysis by means of low-cost setups. Optics and Lasers in Engineering. 2020;134:106158. https://doi.org/10.1016/j.optlaseng.2020.106158

4. Breitenstein O, Warta W, Schubert MC. Lock-in Thermography. Basics and Use for Evaluating Electronic Devices and Materials. Springer Nature Switzerland AG, 2018. 342 p. https://doi.org/10.1007/978-3-319-99825-1

5. Boccardi S. Infrared thermography to monitoring mechanical tests on composite materials: Experimental procedure and data analysis. University of Naples Federico II 2017. http://dx.doi.org/10.6093/UNINA/FEDOA/11750

6. Antolis C, Rajic N. Optical Lock-in Thermography for Structural Health Monitoring – A Study into Infrared Detector Performance. Procedia Engineering. 2017;188:471−478. https://doi.org/10.1016/j.proeng.2017.04.510

7. Shiozawa D, Uchida Y, Kobayashi K, et al. Thermoelastic Stress Analysis and Dissipated Energy Evaluation Using Infrared-Optical Synchronous Measurement. In: Proc. 15th Int. Workshop on Advanced Infrared Technology and Applications. 2019;27:50. https://doi.org/10.3390/proceedings2019027050

8. Akai A, Shiozawa D, Yamada T, et al. Energy Dissipation Measurement in Improved Spatial Resolution Under Fatigue Loading. Experimental Mechanics. 2019;60:181−189. https://doi.org/10.1007/s11340-019-00552-w

9. Sieber L, Urbanek R, Bär J. Crack-Detection in old riveted steel bridge structures. Procedia Structural Integrity. 2019;17:339-346. https://doi.org/10.1016/j.prostr.2019.08.045

10. Chase SB, Adu-Gyamfi Y. Evaluation of fatigue-prone details using a low-cost thermoelastic stress analysis system. Virginia Transportation Research Council; 2016. 53 p.

11. Ciampa F, Mahmoodi P, Pinto F, et al. Recent Advances in Active Infrared Thermography for Non-Destructive Testing of Aerospace Components. Sensors. 2018;18:609. https://doi.org/10.3390/s18020609

12. Oswald-Tranta B. Lock-in inductive thermography for surface crack detection in different metals. Quantitative InfraRed Thermography Journal. 2019;16:276−300. https://doi.org/10.1080/17686733.2019.1592391

13. Vavilov VP, Klimov AG. Teplovizory i ikh primeneniya. Moscow: Intel universal; 2002. 87 p. (In Russ.).

14. Kurilenko GA. Issledovanie povrezhdaemosti metallov termodinamicheskim sposobom. Bulletin of the TPU. 2015;326:105–109 (In Russ.)

15. Boyce BR, Lesniak JR. Thermoelastic Measurement Techniques Enabled by Self-reference. Residual Stress, Thermomechanics & Infrared Imaging, Hybrid Techniques and Inverse Problems. 2019;7:125−127. https://doi.org/10.1007/978-3-319-95074-7_24

16. Izumi Y, Sakagami T, Kubo S. Accuracy improvement of self-reference lock-in thermography method and its application to detection of fatigue cracks in steel bridges. In: Proc. SPIE Conf. on Defense, Security, and Sensing, 2010. Vol. 7661. https://doi.org/10.1117/12.852961

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A. L. Solovyev: development and debugging of the algorithmic part; computational analysis; text preparation; formulation of conclusions. M. E. Royak: academic advising; analysis of the calculation results; the text revision; correction of the conclusions.

*Conflict of interest statement*

The authors do not have any conflict of interest.

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