Integrated thermal flaw detection technology of complex spatial composite structures in operation

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Abstract. The paper presents a complex technology of thermal flaw detection of small-size discontinuity type defects of composite structures. The integrated flaw detection technology is based on the identification of internal defects as sources of heat caused by the use of additional sources of stimulation. The use of complex technology makes it possible to identify types of defects that cannot be detected by the existing methods, for example, defects of small sizes, closed cracks, microcracks, etc. and determine their location in the material. It is shown that the error in determining the depth of defects in the material when using the proposed integrated technology does not exceed 10-15%, which is quite acceptable for practical use.

1. Introduction
The reliability of the operation of structures made of composite materials is largely determined by the presence in the material of internal defects such as discontinuity. This determines the relevance of developing non-destructive testing methods for detecting such defects (cracks, "closed" delamination, and others). The article is devoted to the development of new methods for non-destructive testing of defects that affect the reliability of the operation of structures.

2. Methods, results and discussion
Composite materials have many advantages – strength, lightness, ease of creating structures of complex geometry, and relatively low cost. However, there are also disadvantages, the main of which is the violation of continuity in production and operation of products. The search for such defects is quite a time-consuming task, and there is no exhaustive solution to it, so many mutually complementary methods of checking structures made of composite materials have been developed and used to date.

A common method is radiation monitoring [1]. It is effective for detecting various voids, extraneous materials of various inclusions, structural heterogeneities, such as gaps, breaks of reinforcing elements. However, defects that do not lead to significant changes in the total thickness in the direction of transmission (cracks, delaminations oriented perpendicular to the beam of radiation) cannot be detected by x-ray inspection.

For multilayer glued structures, low-frequency acoustic methods are used, which allow to detect areas of joint failure in multilayer glued structures made of composites based on carbon, boron, glass, organic fibers [2–6]. However, zones with layer disruption that do not have a gap filled with gas are not detected by low-frequency acoustic methods.
The use of computed tomography, which is used for almost any material and objects, is effective. Its development was computer microtomography, which provides a resolution of up to several microns, which makes it possible to identify individual carbon fibers and their breaks in carbon plastics [7]. However, this technology is very expensive, and its scope is limited to the simple geometry of the object.

One of the most promising methods of non-destructive testing is active thermal non-destructive testing, which involves the use of additional sources of thermal stimulation. This method is based on registration and processing using special technologies.

However, the variety of defects in composite structures (CS) requires for their detection and identification of various heat control technologies, each of which solves a certain set of problems.

For example, the problems of identifying small-sized defects such as discontinuity by the depth of their occurrence in the material (determining the depth of defects) in complex spatial structures, the problems of detecting small-sized “closed” defects that have a practically zero opening in the normal state and manifest themselves during loading are currently relevant. Designs by force loads do not allow revealing themselves by traditional technologies, etc.

Methods that solve such problems with varying degrees of certainty have been developed [8-10]. However, for a number of reasons (the physical basis for the formation of temperature anomalies, for example in [11], where the formation of temperature field anomalies is caused by fiber breakage, practical implementation difficulties. For example, to determine the location and size of a defect it is necessary to solve the inverse problem of unsteady heat conduction, knowing the laws of development of dynamic temperature fields [12–15], etc.) have limitations in practical application.

The aim of this study is to develop a new integrated technology of thermal, flaw detection which has a wider scope and relatively simple implementation in practice, which allows detecting and identifying small and “closed” defects in complex composite structures.

Recently, the method (technology) of ultrasonic thermography has been increasingly used [16, 17]. Its advantage over existing methods is that it “presents” internal defects such as discontinuities caused by local autonomous internal heat sources. This allows them to be reliably detected by analyzing the temperature field of the surface of the product: by registering the temperature field on the surface, you can determine the location of the energy concentrator in the material relative to the surface of the product. Further, for example, having solved the inverse problem of unsteady heat conduction, it is possible to determine the location and size of the defect [15].

On its basis, one of the technologies of complex thermal flaw detection, the technology of ultrasonic thermotomography, was developed [18].

The technology of ultrasonic thermotomography is most relevant for detecting internal small-sized defects and determining their depth in structures with complex geometric shapes.

The essence of the method is to register with a thermographic equipment changes in temperature field anomalies when excited by ultrasonic vibrations [16] on two opposite surfaces of the material and determining the location of an internal defect by its depth based on the difference in the characteristics of temperature fields on two opposite surfaces.

The temperature field formed in the region of the internal defect propagates according to the laws of thermophysics in the material of the product in accordance with the heat equation:

$$c_p \frac{\partial T}{\partial t} + \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = q(t,x,y,z)$$  (1)

where $c$ is the specific heat, $\rho$ is the density, $\lambda$ is the thermal conductivity, $T$ is the temperature measured from the temperature of the medium, $t$ is the time from the start of heating, $q$ is the specific power of the heat source per unit volume.

On the surfaces of the test sample in the form of a plate, the boundary condition of free convection takes place:

$$ \pm \lambda \frac{\partial T}{\partial z} = \alpha T,$$
where $\alpha$ is the coefficient of convective heat transfer to air, the plus sign is selected on the lower surface of the plate $z = -H/2$, “minus” on the upper surface $z = H/2$, where $H$ is the thickness of the plate.

The initial temperature at all internal and boundary points is equal to the temperature of the medium:

$$T(0, x, y, z) = 0.$$  

Computational and experimental studies have shown that the dependence of the time to reach the maximum temperature on the depth of the defect is quite accurately described by a parabola of the second degree:

$$t_{opt} = V \left( \frac{h}{H} \right)^2,$$

where $V$ is the coefficient of proportionality.

The time to reach the maximum temperature at a surface point at a distance $h$ will be equal to:

$$t_{opt1} = h^2/V,$$

whence $V = h^2/t_{opt1}$.

Accordingly, you can write

$$V = (H - h)^2/t_{opt2}.$$

Equating the right sides of the equations, we obtain

$$h^2/t_{opt1} = (H - h)^2/t_{opt2}.$$

Solving this equation, we obtain:

$$h = H \frac{\sqrt{t_{opt1}}}{\sqrt{t_{opt1}} + \sqrt{t_{opt2}}} \quad (2)$$

Thus, knowing the values of $t_{min}$, $t_{max}$ and the plate thickness $H$, we can determine the depth of the defect $h$.

The advantage of this technology over the existing ones is the following: there is no binding to the manufacturing technology of products from PCM, a fairly simple mathematical apparatus and a simple practical implementation.

Experimental studies were carried out at the stand (figure 1). The studied product (4) was a flat PCM sample 200 × 200 mm in size and 15 mm thick. An artificial defect with a diameter of 25 mm at a depth of 7 ± 0.5 mm is laid in the center of the product during its manufacture.

The presence of two mirrors (1) and (2) is due to the need to register temperature fields from two surfaces of the controlled product (4) at the same time points in order to eliminate the error caused by the change in the recorded temperature field on the surfaces in time. This is especially true for materials with high thermal conductivity.

Mechanical (low-frequency ultrasonic) oscillations with a frequency of 22 KHz were introduced into the product (4). The generator UZDN-2T was used, the electric power of 1000 watts. The temperature field was recorded by IRTIS-2000 thermographic equipment from two surfaces simultaneously and processed in accordance with the above theory. The frequency of recording thermograms was 2 Hz. For clarity and simplification of the calibration of thermographic equipment, the zone for introducing ultrasonic vibrations into the product is “cut out” in the above thermograms ultrasonic vibrations in the product on the above thermograms “cut out”.

To illustrate figure 2 shows some thermograms obtained in the process of experimental studies. Thermograms consist of two parts. The left part is a thermogram of a surface “close” at a distance $(H-h)$ to the defect. The right part is a thermogram of the surface, “distant” (at a distance $h$) from the defect.
**Figure 1.** A stand for experimental studies: 1, 2 – stainless steel mirrors, 3 – a place for introducing ultrasonic vibrations to create an internal heat source, 4 – a product under investigation, 5 – a thermograph (IRTIS-2000), 6 – field of view of a thermograph, 7 – thermogram of the test product.

**Figure 2.** Experimental thermograms: (a) 50 s, (b) 100 s, (c) 150 s, (d) 200 s from the start of heating.
Figure 3 shows an experimental graph of temperature changes on the surfaces of the product.

![Graph of temperature changes on the product surfaces](image)

**Figure 3.** Graphs of temperature changes on the product surfaces: the upper curve is the surface closest to the defect (T (city C) – B), the lower curve is the surface T (city C) – D farthest from the defect.

Figures 2 and 3 clearly show that the near side heats up faster than the far side. Experimentally was obtained:

\[ t_{e\text{opt}1} = 150.0 \text{ s}, \quad t_{e\text{opt}2} = 280.0 \text{ s}. \]

Thus, the depth of the defect is:

\[ h = 15 \text{ mm} \frac{\sqrt{150}}{\sqrt{150} + \sqrt{280}} = 6.13 \text{ mm}. \]

The relative error in determining the depth is:

\[ \xi = (7 \text{ mm} - 6.13 \text{ mm}) / 7 \text{ mm} \times 100\% = 12.4\%. \]

The resulting error in determining the depth is quite acceptable for use in practice.

The above control technology has several advantages over the existing ones, but it is not effective enough to detect defects such as “microcracks” and “closed” defects that can be distributed over a large area of the product, and whose temperature fields are less contrasted. To detect and identify defects of this type, the technology of thermal defectometry - electrical power thermography [19] was developed.

Electrical power thermography is based on the sensitivity of the physical properties of the material and defects, for example, electrical resistance, to the degree of change in the characteristics of defects when a load is applied: when a structure made of composite materials (CM) is exposed to electric current and the load is applied, which leads to a change in the characteristics of defects, for example, crack opening, the electrical resistance of the defective areas increases, which leads to an increase in heat generation in these areas.

In other words, the peculiarity of stimulating heat generation by electric current with simultaneous mechanical loading is the appearance of point sources at the tops of cracks, while under ultrasonic action, as it is known; the main source of heat is the friction of the edges of cracks [6].

By registering the temperature field with thermographic means, internal defects are determined and identified.
Consider a certain volume of material through which direct current flows with density $j$. Therefore, it is true:

\[
\begin{align*}
\text{div } j &= 0; \\
\frac{\rho}{E} \nabla E &= j,
\end{align*}
\]

where $j$ is the current density, $\rho$ is electrical resistivity, $E$ is the electric potential.

An electric current in a conductive medium causes heat generation. The intensity of the heat source (power released per unit volume) is determined by the Joule-Lenz law:

\[ f = \rho j^2, \]

therefore, the heat equation for the region with a passing electric current will take the form:

\[ \frac{\partial T}{\partial \tau} - \alpha^2 \nabla^2 T = \rho j^2, \]

where $\alpha$ is the coefficient of thermal diffusivity, $\tau$ is the time, $T$ is the temperature.

In a thin-walled structural element, the opening of cracks oriented at an angle to the current density vector can be considered equivalent to a decrease in the cross-sectional area. Then, as a first approximation, we can use the results of [20], in which the heating of a section of a smaller cross section is described by the formula:

\[
T_{m} = \frac{J m \rho l_{m} s_{m} + 2 \lambda s^2 J^2 \rho}{k_{F} F_{m} S_{m} \sqrt{\lambda s}},
\]

where $J$ and $J_m$ are the current densities in the sections of the main section and the smaller section; $S$ and $S_m$ sections of the main and reduced in size areas; $F$ and $F_m$ is the cooling surface of the conductor of the main and reduced in size sections; $\rho$ – specific resistance of the conductor; $\lambda$ is coefficient of thermal conductivity of the material of the conductor; $k_T$ is heat transfer coefficient.

An estimate by formula (6) shows that a decrease in the cross-sectional area leads to a slight increase in temperature.

Solving the system of equations (3) similarly to [21] by mapping the exterior of the ellipse to the exterior of the circle; complex potential is determined:

\[
w(z) = \frac{1}{2} j_\infty \cdot \left[ z + \sqrt{z^2 + b^2 - a^2} - \frac{a + b}{b - a} \left( z - \sqrt{z^2 + b^2 - a^2} \right) \right],
\]

where $z = x + iy$, and the current density is found as the gradient of the real part (7).

In the limit, the current density distribution in the vicinity of the crack is obtained. So, for $x = 0$ we have:

\[ j_x = j_\infty \frac{y}{\sqrt{y^2 - b^2}}. \]

Formula (8) can be transformed by replacement: $y = b + \Delta r$ to the form that determines the asymptotic behavior of the current density at the crack tip:

\[ j_x = \frac{b + \Delta r}{\sqrt{\Delta r^2 + 2b\cdot\Delta r}} \approx j_\infty \frac{\sqrt{b}}{\sqrt{2\Delta r}}, \]

As can be seen, the current density is concentrated at the crack tip. Here $\Delta r$ is the change in the distance from the crack tip.

According to the Joule-Lenz law (4), the heat release intensity is proportional to the square of the current density, i.e.
and equation (5) takes the form:

$$\frac{\partial T}{\partial \tau} - \alpha^2 \nabla^2 T = \rho \frac{j_x}{2\Delta r}. \quad (10)$$

The fundamental solution of equation (11) has the form:

$$T(\Delta r, \tau) = \frac{q}{4\pi\alpha \cdot \Delta r} \erfc \left( \frac{\Delta r}{\sqrt{4\alpha \tau}} \right). \quad (12)$$

where \(\erfc\) is an additional error function, \(q\) is the power of the heat source in the vicinity of the crack tip.

Figure 4 shows a graph of the temperature on the surface of the sample in the crack area versus time for various crack sizes and an initial temperature of 20 °C. The width of the plate \(B\) was assumed to be fixed and equal to twice the length of the crack, the current value \(I = j_x B\)

As a result, we obtain a significant increase in temperature in the crack region of very small sizes, and the increase in temperature change is proportional to the length of the opened crack.

Experimental studies were carried out on the setup shown in figure 5.

As the object of study, a carbon fiber mesh construction with an internal defect such as a crack was used (figure 6). It was fixed along two opposite edges and bent by a shear force in the center to increase crack opening (figure 5).

A constant current of 0.3 to 5 A was applied to the edges of the product.

At the initial stage of the experiment, before application and at the initial stage of application of the load, the temperature of the sample over the entire surface did not change significantly, despite the presence of a crack.

The constant transmitted current did not cause a change in the temperature of the grid surface, since the crack remained “closed”.

However, when a mechanical load was applied, cracks in the ribs opened, which 5 seconds after the start of the load application caused a temperature change and the appearance of noticeable heat spots. Further, from the application of a mechanical load, both the sizes of the regions of elevated temperature recorded on the thermogram and the temperature in the crack region increased. After removing the load, the temperature in these areas gradually decreases.
**Figure 5.** Photograph of the experimental setup.

**Figure 6.** Photograph of a fragment of the test sample (mesh construction) from CM.
Figure 7 shows the thermograms of the surface of the test sample during the experiment.

**Figure 7.** Thermograms recorded during the experiment: 1–6 – sequential in time (the magnitude of the applied load) video images of the temperature field during loading and unloading. Figure 8 shows a graph of temperature versus time, obtained calculations and experimental results.
Figure 8. Dependence of temperature on time at the value of the applied load 100N: solid line – experimental results, dotted line – the results of theoretical modeling.

Comparing the graphs of the results and experimental studies (figure 8), it can be seen that the behavior of the curves is the same. The difference between the obtained theoretical and experimental values does not exceed 15%. This indicates, firstly, the adequacy of the physical and mathematical model that describes the process of electric power thermography, and secondly, the reality and stability of the proposed control method and the possibility of its application in practice, because it is reliably described by a mathematical model.

3. Conclusion
An integrated technology of thermal defectometry of small defects such as discontinuity of composite structures of complex shape, including ultrasonic thermo-tomography and electric power thermography, has been developed. The technology of complex defectometry is based on the identification and identification of internal defects as sources of heat caused by the use of additional sources of stimulation. The use of complex technology makes it possible to identify types of defects that were practically not detected by existing methods, for example, defects of small sizes, closed cracks, microcracks, etc. and determine their location in the material. It is shown that the error in determining the depth of defects in the material when using the proposed integrated technology does not exceed 10–15%, which is quite acceptable for practical use.

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