Determination of the temperature coefficient of linear expansion by processing of the interferograms

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Abstract. In this paper the theoretical and experimental justification of the simple high-precision method of determining the temperature coefficient of linear expansion of the holographic or digital speckle interferometry are presented. The interferogram is proposed to register under bending thermoelastic deformations of the sample caused by the temperature difference through thickness. The proposed method is contactless and does not impose special requirements to the surface material as in the case of classical interferometry. Is numerical modelling of thermoelastic deformations of the sample, confirming the correctness of the proposed method.

1. Introduction

The composition materials were widely adopted in the space industry in communication by essential advantage the weight and stiffness characteristics at design and creation of products. In the work [1] feature of the situation in which there is the materials science oriented to problems of modern composition materials is noted. It is in what rates of studying of properties of these materials is practically not in time behind their creation. Researches of properties of new composition materials – the expensive and labor-consuming task. Its successful decision is provided when sharing both theoretical, and experimental methods. Are the part of many composition materials binding (for example, in the form of glue) which cannot be subject to influence of high temperatures. Besides some composition materials are plates or covers which thickness is much less than their other parameters. Also composition materials has explicit anisotropy of physical and mechanical properties.

One of important characteristics of the materials working in difficult conditions is the temperature coefficient of linear expansion (TCLE) causing relative change of the sizes of the body at variable temperatures that in turn can lead to violation of operability of the design. Accounting of TCLE is necessary practically in all modern industries of equipment and technologies using exact interface of the parts operated at variable temperatures.

Due to these circumstances development of experimental research techniques of behavior of TCLE is actual at variable temperatures. These experimental methods have to possess high metrological characteristics, provide the possibility of measurements of the deformed state on all surface of object of research, and have the high level of automation and information capacity.

In the works [2,3] the wide overview of methods of measurement of TCLE is carried out. It is noted that as TCLE of the majority of materials is in the range (10-7-10-6) °C⁻¹, measurement of this coefficient demands use of high-precision and highly sensitive measuring instruments. Most fully
optical methods of measurements, especially methods of the interferometric holography, and also the correlation digital speckle interferometry which gained development on their basis which allow to perform measurements on materials without preliminary processing of the surface conform to the listed requirements and do not demand use of the additional optical elements connected with the studied material.

The international standard from ASTM [4] in which is known the method of definition of TCLE which is that process of temperature lengthening is registered by means of the Michelson interferometer or Fizo in both cases is described lengthening of the sample is determined by interferograms. The interferogram is formed at the expense of the arisen phase difference between the optical element connected with the studied object changing the sizes and rigid basis. It is possible to refer need of contact interaction of the optical element to shortcomings of this method, being at the sample end face that breaks purity of experiment. In the work [5] the speckle interferometry method for contactless definition of temperature expansion of nanomaterials with the rough surface is considered. Ratios for calculation of key parameters of optical-electronic system the speckle interferometer on the basis of the optical scheme of the Michelson interferometer are given. However in this work the optical scheme of registration of interferograms is constructed according to the optical scheme as in the work [6] and, therefore, is inherent in this way similar shortcoming.

Thus, the improvement of methods for measuring of the temperature coefficient of linear expansion, especially for anisotropic materials, is an urgent task.

Special attention is now being given to the expanding of the scope of the coherent optics methods, and in particular, interferometric techniques. Interferometric methods such as holographic and speckle interferometry are unique noncontact measurement technologies that allow to simultaneously control the displacement of points along the entire observed surface of the object. In addition, holographic and speckle interferometry does not impose strict requirements for the quality of the surface under study, unlike classical interferometry [7-12].

In this paper the theoretical and experimental justification of the simple high-precision method of determining the temperature coefficient of linear expansion of the materials as isotropic and anisotropic in the processing of interferograms obtained by holographic or digital speckle interferometry are presented.

2. Method the determination of TCLE by bent deformations

It is known that impact of an uneven thermal stream on material leads into bend deformations of the studied object. Let's make numerical experiment in finite elements of software NASTRAN for a sample in the form of the disk made of isotropic and anisotropic material. The scheme of thermal loading of the studied sample and modeling of a bend of a sample was supposed at linear distribution of temperature on thickness of a sample and uniform thermal heating of one surface of a disk. Boundary conditions were modeled so that to provide summary expansion and a bend of a sample. In figure 1 results of numerical experiment are presented.

![Figure 1. a) Results of numerical modeling of a temperature bend of isotropic material; b) anisotropic material.](image-url)
From numerical experiment it is visible (figure 1) that at temperature deformation the sample bend form at isotropic material takes the sphere segment form, and at anisotropic material the ellipsoid calotte. The equidistant fringes characterizing identical movement of the disk at the thermal bend of rather initial state are also presented in figure 1. Apparently they represent concentric circles for isotropic material and family of elliptic curves for anisotropic material.

Let’s consider interrelation between the spherical shape of the bend of the studied sample connected with TCLE, and the ring form of equidistant fringes. For calculation of TCLE it is representable the diametrical section of the flexural spherical surface of the studied sample and graphical representation of the form, equidistant fringes with radiuses of \( r_n \) and \( r_m \) where \( n \) and \( m \) – numbers of equidistant fringes counted from edge of the disk (figure 2).

Figure 2. a) Estimation scheme; b) determination a radius of the ring of the interferogram.

According to Kirchhoff’s hypotheses, in case of thin plates, the normal to the middle plane at the bend remains rectilinear and normal to the deformed middle of the surface, in work of authors [13] expression for definition of TCLE (\( \alpha \)) of material in the following look is received:

\[
\alpha = \frac{1}{\frac{\Delta T_{21}}{\Delta T_{10}} \frac{\rho}{\delta}} ,
\]

where \( \Delta T_{21} = T_2 - T_1 \), \( \Delta T_{10} = T_1 - T_0 \), \( \delta \) – sample thickness, \( \rho \) – radius vector of curvature of the surface. Thus, for definition of TCLE it is necessary to know the radius of curvature of the bend of the surface, thickness \( \delta \) the studied sample which is connected with temperature drop on thickness of the sample and value of temperatures on surfaces of the studied disk.

When heating the sample except its bend initial thickness \( \delta_0 \) changes. It will be pertinent to assume that initial thickness \( \delta_0 \) and \( \delta \) after deformation with the fine precision are equal as the sample thickening at the expense of thermal expansion is not enough because TCLE for the majority of materials is in the range \((10^{-7}-10^{-6})^\circ C^{-1}\).

For the solution of the objective, we will consider communication of radius of curvature \( \rho \) the surface bend with radiuses of \( r_n \) and \( r_m \) of equidistant fringes. Follows from the scheme of the bend of the studied sample presented in figure 2a that the curvature radius vector characterizing the sample bend is defined by radiuses of \( r_n \) and \( r_m \) of equidistant fringes following formulas:

\[
\rho^2 = x_m^2 + r_m^2 ,
\]

\[
\rho^2 = x_n^2 + r_n^2 ,
\]

\[
x_m = x_n + \Delta h_{nm} ,
\]

where \( \Delta h_{nm} \) – the high-rise difference between equidistant fringes with radiuses of \( r_n \) and \( r_m \), and also we will consider that in our consideration \( m > n \).

Solving system of equations formed by expressions (2-4) for the radius vector of curvature we will receive the following expression:
Thus communication between curvature radius vector, characterizing the sample bend, and radiuses of equidistant fringes, and also the high-rise difference between equidistant fringes is received. These sizes can be determined by interferometric measurements.

3. Technique of definition of TCLE by the processing of the interferograms

Registration of band deformations by methods digital holography or speckle interferometry allows to record interference figures which bear information into band deformations of the studied sample and in our case will correspond to equidistant pictures, described above. It is known that holographic also as the speckle interferograms is the alternation of bright and dark fringes. To each fringe there corresponds displacement of $u_{n}$ of rather initial state and which is defined by the following expressions [7,8] for the dark fringes in the speckle interferometry:

$$u_{n}^{\text{dark}} = \frac{n \lambda}{2}, \quad n = 0; \pm 1; \pm 2;\ldots;$$

where $\lambda$ – the wavelength of laser radiation, $n$ – the order of fringes.

For the holographic interferometry the ratio (1) is carried out for bright fringes, and the ratio (2) is respectively carried out for dark fringes. These ratios correspond to the optical scheme of registration of interferograms in which the direction of lighting by the coherent radiation of the studied sample and the direction of registration match that to similarly optical scheme of the Michelson interferometer.

For development of the computational method of TCLE according to interferograms we will consider the scheme of thermal loading of the studied sample and the optical scheme of registration of the interferograms presented in figure 3a. The studied sample 1 is located freely on the rigid basis 3. At uniform thermal loading 4 these samples on the one side, there will be its bend from position 1 (not deformed state) to position 2 (deformed state – the bend). The surface of the bend will represent the spherical surface for isotropic materials and the curvilinear surface when testing anisotropic materials. In figure 3b it is presented typical the speckle interferogram of the bend of the studied sample as a result of uniform thermal loading [14]. The dark and light fringes on the holographic or speckle interferograms are equidistant lines characterizing the equal displacement at bending of the test sample relative to its initial (unloaded) state. Therefore, $\Delta h_{nm}$ – the high-rise difference between equidistant lines characterizing the equal displacement at bending of the test sample relative to its initial (unloaded) state with radiuses of $r_n$ and $r_m$ can be expressed through the values of the displacement $u_{m}$ and $u_{n}$ obtained by the measurement of the interference fringes radiuses from holographic or speckle interferograms:

$$\Delta h_{nm} = u_{m}^{\text{dark}} - u_{n}^{\text{dark}} = u_{m}^{\text{bright}} - u_{n}^{\text{bright}} = \frac{\lambda}{2} (m-n), \quad m = 0; \pm 1;\ldots\quad n = 0; \pm 1;\ldots;$$

Thus, using the equations (1), (5) and (8), for definition of TCLE we will receive the following equation at measurement of radiuses of dark or bright fringes on the holographic or speckle interferograms:

$$\alpha = \frac{1}{\Delta T_{21} \frac{\partial T}{\partial \theta} \left( r_n^2 + \left( \frac{r_n^2 - r_m^2}{\lambda (m-n)} \right)^2 \right)^{1/2} - \Delta T_{10}}$$

Equation (9) allows calculating TCLE by measurement of two different radiuses of interference fringes on the holographic or speckling interferograms.
Figure 3. a) The experimental scheme with the Michelson interferometer: 1 – not deformed state of the sample; 2 – the deformed state of the sample; 3 – rigid basis; 4 – heat flow; 5 – laser; 6 – collimator; 7 – beam splitter; 8 – basic mirror; 9 – video camera or photographic material.
b) Characteristic speckle interferogram of the temperature bend of the honeycomb sample (laminate).

To lower the role of systematic errors and to increase the accuracy of definition of TCLE it is possible if TCLE to define through the arithmetic average at measurement of several radiuses of fringes, and \( m \) and \( n \) are not obliged to be near standing therefore it is possible to create rather large number of combinations of differences of radiuses. Apart from that, the accuracy and reliability of the received results can be increased due to post-processing of the holographic or speckle interferograms. In the article \[15\] the methods of contrast increasing of the interference patterns in digital holographic interferometry by numerical linear phase modulation and interpolation post-processing of digital focused-image holograms are discussed. In both cases it becomes possible to separate an extended frequency range of the restored object field and, thus, significantly reduce the speckle size in the reconstructed object image, also increasing the fringe contrast in the interferograms.

4. Conclusion

A method on the basis of holographic or speckle interferometry registering in the contactless way the temperature deformations representing the sample bend for definition of TCLE of samples of materials with the rough surface is offered.

The accuracy and reliability of the received results can be increased due to statistical processing of the large number of radiuses of fringes on the speckle interferograms.

In the offered way it is possible to receive TCLE both for isotropic materials, and for anisotropic materials. In case of anisotropic materials it is necessary to make calculation in different diametrical sections of the bend of the curvilinear surface.

The developed method significantly expands possibilities of measurements of TCLE of both isotropic, and anisotropic materials, and supplements classical interferential methods of the dilatometry as allows to measure properties of samples which research was represented difficult.

5. References

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