Application of the spectral-correlation method for diagnostics of cellulose paper

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Abstract. The spectral-correlation method was described for diagnostics of optically inhomogeneous biological objects and materials of natural origin. The interrelation between parameters of the studied objects and parameters of the cross correlation function of speckle patterns produced by scattering of coherent light at different wavelengths is shown for thickness, optical density and internal structure of the material. A detailed study was performed for cellulose electric insulating paper with different parameters.

1. Introduction

Determination of physical properties of biological objects by contact methods is difficult or impossible in many cases. Therefore, the application of non-destructive contactless methods, in particular, spectral-correlation method [1-2], for diagnostics of biological objects is very important. Of particular importance in high voltage technique has electrical insulation based on cellulose of plant origin, as well as prospective bacterial cellulose. The use of spectral-correlation method gives the opportunity to measure some of the parameters of different biological objects and materials in the process of exposure to different factors, in particular, in the artificial aging. We can assume that the use of this method will expand the possibilities of the study of biological objects and materials and will improve their performance.

2. Basic principles of the spectral-correlation method

Spectral correlation method of diagnosis is based on finding statistical regularities of speckles produced by scattering of coherent light at changing the wavelength ($\lambda$) of the probing radiation. Cross-correlation functions (CCF) of the intensity distributions of the scattered radiation at different wavelengths [1-2] were calculated for this purpose:

$$CCF(\Delta x, \Delta y) = \frac{1}{4x_s y_s} \int_{y_0-y_s}^{y_0+y_s} \int_{x_0-x_s}^{x_0+x_s} I_{\lambda_1}(x, y)I_{\lambda_2}(x-\Delta x, y-\Delta y)dxdy$$

(1)

where $x_0$, $y_0$, $x_s$, $y_s$ – are the coordinates of the centre of integrating area and halfwidth of the area, $I_{\lambda_1}$, $I_{\lambda_2}$ are the intensity distributions at wavelengths $\lambda_1$ and $\lambda_2$. At usage of the CCD camera with the size of the matrix 736x572 pixels, the values $x_s$ and $y_s$ were chosen 50 pixels. It has allowed us consider speckles within the limits of the area of integrating like isotropic, and too, quantity of speckles are sufficient for correct calculation of the CCF.
It is known that the spots of speckles of a scattered radiation when changing the wavelength of the radiation acquire directional movement and the transformation of the shape [2]. Directed movement depends on the angle of scattering and does not depend on the parameters of the scatterer. Therefore, it is of not interesting for this work.

Transformation of speckles (“boiling speckles”) depends on the optical characteristics of the scattering object. In order to separate these two effects, the search of the maximum value of CCF (by two parameters – $\Delta x$, $\Delta y$) at each wavelength ($\lambda_2$) was used. The dependences CCF$_{max}$ on the wavelength can be considered as independent on the scattering angle, respectively, depending only on the scattering properties of the investigating surface.

The CCF and CCF$_{max}$ parameters (the width and form of dependence) are characteristics of optical inhomogeneities of the investigated objects. The more the longitudinal typical size of the optical inhomogeneities of the object, the more narrow characteristic range of variation of the CCF$_{max}$. There are other methods of processing of imaging of the speckles, such as [3-4].

3. Experimental setup
In this work, semiconductor laser ($\lambda \approx 650$ nm) was used as the radiation source. The wavelength tuning is carried out by changing the temperature of the heterojunction using the Peltier element [1, 6]. The CCD television camera was used to register distribution of intensity of radiation scattered by the investigated sample. The angle of incidence of the probing beam relative to the normal to the surface of the paper was 10 - 30 degrees. The intensity distribution of diffuse scattered radiation is produced approximately in the direction of specular reflection. Processing of the obtained images was performed with a personal computer connected to the television camera. The gauge dependence of $\lambda$ on temperature $T$ was measured experimentally using the spectrometer “Avantes-20148”. The degree of polymerization of the cellulose was determined for aged samples of the paper, and images of the fiber structure (Fig. 1b) were obtained using a scanning electron microscope (SEM).

4. Data obtained
The CCF study were conducted on samples of insulating paper of various types (made from pulp of coniferous trees, as well as bacterial cellulose) and thickness of both new and artificially aged according to the method [5]. The paper samples with different density were investigated also. An example of the obtained dependences is shown in Figure 1a.

![Figure 1a](image1.png)

**Figure 1 (a, b). (a)** CCF$_{max}$ for insulating paper thickness of: 1 – 40 $\mu$m, 2 – 175 $\mu$m; (b) The structure of the paper after thermal aging for about 240 hours at 140$^\circ$C. The destruction of the structure of the paper is visible.
Figure 2 (a, b). (a) $C_{\text{CF}}_{\text{max}}$ for insulating paper K140 after thermal aging for about 240 hours at 140°C: 1–3 – three measurements in the same area, 4 – measurement at the different area of the sample; (b) The change of the CCF at the thermal aging process of insulation paper: 1 – new (before thermal aging), 2 – after 170 h, 3 – after 530 h.

The half-width of the dependence CCF (Figure 1a) for the paper with thickness of 40 µm is substantially greater than that for the paper with thickness of 175 µm, which confirm the regularity mentioned above. However, the ratio of the obtained values of half-width of CCFs is significantly smaller than the ratio of the sample thickness of the papers.

Figure 3 (a, b). (a) $C_{\text{CF}}_{\text{max}}$ for new (before thermal aging) insulating paper: 1 – K140 (Rus), 2 – DLZ-130 (produced by Henglong Plastics, China), 3 – experimental sample with a reduced density (ESRD) of the cellulose fibres; (b, c) The structure of the paper of the paper obtained using SEM: (b) – DLZ-130, (c) – ESRD.
This may be explained by the penetration of light not the entire thickness of the paper. We have investigated the reproducibility of measurement of $CCF_{\text{max}}$ to assess the reliability of the obtained results (Figure 2). For these purposes, distribution of scattered intensity on the same area of illuminated paper surface (type K140) was three times measured at 50 – 60 wavelengths. The CCFs were determined based on the distributions. The measurement of the CCF for the other area of the surface of the paper was carried out also. The calculated $CCF_{\text{max}}$ are shown in the Figure 2. As follows from the graphs, there is good reproducibility of the results. Therefore, at case of a significant difference between the CCF parameters of different samples the parameters of the paper can be considered as different. Figure 3 shows the dependence of CCF (Figure 3a) on the structure of the paper. We also fulfilled a comparison of CCF for the scattered radiation of the cable paper K140 (light brown) and the electrically conductive cable paper with the carbon filler in the form of soot (black). A large half-width of the $CCF_{\text{max}}$ of the black paper caused by the greater magnitude of the absorption of the radiation in the paper, respectively, the smaller the penetration depth of the radiation (Figure 4a). A significant difference of $CCF_{\text{max}}$ has dry and oil-impregnated insulation paper (Figure 4b).

The obtained data confirm the basic principles mentioned above: the relationship of thickness, density and structure of the paper, as well as the parameters of the impregnation composition with the parameters of the CCF. The results showed the possibility of using spectral correlation method for the diagnosis of paper-impregnated high-voltage insulation, in particular insulation of power transformers, as well as other optically heterogeneous biological objects.

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