SPATIAL FILTERING OF PARTIALLY COHERENT IMAGES

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RÉSUMÉ

Des particularités de filtration spatiale d'images partiellement cohérentes ont été étudiées. La méthode d'analogies radiooptiques nécessaire à analyser le fonctionnement d'un système optique a été utilisée à cet effet. L'expression numérique d'une fonction optique de transfert pour une cohérence arbitraire de champ d'éclairage auxiliaire, pour une forme de facteurs d'ouverture et pour un paramètre de défocalisation a été calculée et étudiée. Une installation de laboratoire expérimentale utilisant une source d'éclairage auxiliaire à cohérence variable a démontré l'efficacité de filtration spatiale d'images partiellement cohérentes.

ABSTRACT

Features of spatial filtering of partially coherent images are investigated. A radiooptical analogy method for analysis of optical system operation is used. Analytic expression of optical transfer function for arbitrary coherence of illumination field, for arbitrary aperture factors and for arbitrary defocusing parameter is deduced and investigated by numerical methods. Efficiency of spatial filtering of partially coherent images has been showed by laboratory experimental system using illumination source with tunable coherence.

1. INTRODUCTION

In this paper the features of spatial filtering of partially coherent images are investigated by means of an optical system. Particular attention is given to suppression of field of direct illumination. This filtering known as the dark field method (DFM) has a great practical interest for problem of observation of weakly reflected large objects in inhomogeneous medium. To all appearance, the most detailed and profound analysis of partially coherent image construction was performed by Hopkins. The similar analysis is used in the present paper in which problems of the illumination field suppression (the DFM for a partially coherent field) are investigated for construction of images of weakly scattering objects. We consider the case when spatial coherence of illumination field is finite due to using self-luminous source. In these conditions the optical transfer function (OTF) is determined by a source size, and by an aperture factor depending on size and form of spatial filters.

For experimental test the special source with tunable coherence was designed in the laboratory. The important feature of the experimental system is the way of OTF measurement for arbitrary forms of spatial filters. For partially coherent illumination the imaging system is linear neither for complex amplitudes nor for intensity. It does not allow to use the known methods of OTF measurements. Therefore special method of OTF measurement has been devised. The main idea consists in measurements of spatial components of an output signal which is given on the system entrance. The generation of the input spatial component and the analysis of output spatial component is realized by synchronously generated moire patterns. Every moire pattern is obtained by rotation of crossed diffraction gratings. Theoretical and experimental dependence of contrast range of spa-

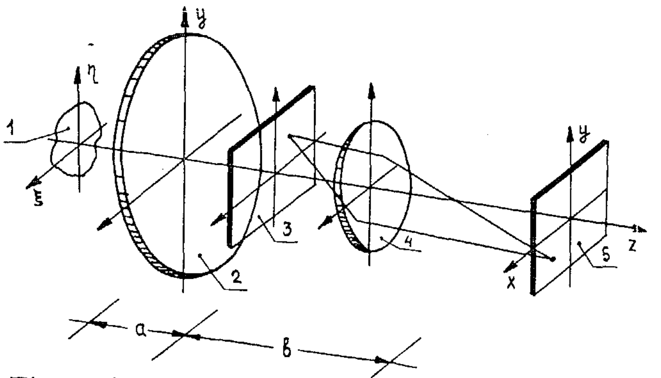

Figure 1: Structure of optical system of spatial filtering of partially coherent images (1-source of partially coherent illumination; 2-condensor; 3-input plane; 4-lens; 5-output plane)

tial component on the illumination source size for defocusing is of interest. Measurements of contrast range of certain spatial component for defocusing allows to measure the source coherence function then spatial distribution of source intensity can be obtained by Fourier transformation according to the van Cittert-Zernike theorem.

2. PARTIALLY COHERENT IMAGING SYSTEM

Consider the features of image construction, for example, by a simplest optical system. This system consists of a lens and two parts of free space: between input plane $p(x,y)$ and plane contiguous to the left of lens $p_a(x,y)$, between plane contiguous to the right of lens $P_a(x,y)$ and output plane $P_b(x,y)$ (see Fig. 1). In similar system the illumination scheme of observation object isn't specified. The observation object is placed into the input plane at a distance a away from lens. When optical system is used for observation of objects in atmosphere, illumination field in the input plane can be considered as plane or quasi-plane. This circumstance can lead to some limitation of field of vision of optical system. In optical filtering systems the illumination of input plane can be realized by focusing wave lifting the limitation on region of vision.

For analysis of optical system operation for partially coherent illumination we will use the results of Hopkins. Note that the source length, lens aberration, medium random inhomogeneities lead to the disturbance of wave sphericity in expressions for $P_{bc} = P_b(x,y)e^{i\frac{k}{2b}(x^2+y^2)}$ (quasi-spherical focusing wave can be identified as input image) and ${P_{ac}}^b$ (as output image) and so the formula for the real lens will be incorrect. For correction of these effects we assume that point source displaces relatively optical axes in such way that image displaces from the lens L center to the point (x_0, y_0). It gives additional phase modulation of input distribution, which can be defined by the factor $e^{ik(x\sin\varphi+y\sin\Psi)}$, where φ and Ψ are displacement angles. In our case they can be defined as $\sin\varphi \sim \frac{x_0}{a}, \sin\Psi \sim \frac{y_0}{a}$. Then the factor determining the additional modulation will have the form: $e^{\frac{ik(xx_0+yy_0)}{a}}$. If source size or lens aberration including distortion by medium lead to violation of point-conditions: $x_0 \ll a\lambda D_x^{-1}$, $y_0 \ll a\lambda D_y^{-1}$, then observation results will be presented as a sum of images determined by the all point sources. In this case we have for the resulting image intensity:

$$< |P_b(x,y)|^2 >= \frac{k^2}{4\pi^2 b^2} \int\limits_{-\infty}^{+\infty} \int\limits_{-\infty}^{+\infty} F(\xi,\eta)$$

$$| \int\limits_{-\infty}^{+\infty} \int\limits_{-\infty}^{+\infty} P_{ac}^b(x',y') e^{i\frac{k}{b}(x'\xi+y'\eta)} C_M(\frac{k}{b}(x-x'),$$

$$\frac{k}{b}(y-y'))dx'\,dy'|^2 d\xi\,d\eta \tag{1}$$

where C_M is Fourier-transformation of aperture function of lens $M(x,y)$, $k = \frac{\lambda}{2\pi}$, λ is the wave length. Function $F(\xi,\eta)$ defines the intensity distribution in illumination plane (Fig. 1). If $F(\xi,\eta) = A_0\delta(\xi)\delta(\eta)$ and the source is a point source , from (1) we can obtain the formula determining the optical system operation for coherence illumination. Otherwise, if the source has length and $F(\xi,\eta) = 1$, formula for the non-coherent illumination follows from (1). On the basis of (1), the concept of CTF can be generalized for optical system with a partially coherent illumination. For this purpose we found out the optical system response on the input signal described as: ${P_{ac}}^b(x,y) = e^{i(xu+yv)} + e^{-i(xu+yv)}$. Substituting this signal in (1), we have the expression for CTF of optical system considered here:

$$K_f = \frac{e^{\frac{-ib^2(u^2+v^2)\Delta}{2k}}}{4\pi^2} \int\limits_{-\infty}^{+\infty} \int\limits_{-\infty}^{+\infty} F(\frac{b}{k}u', \frac{b}{k}v')$$

$$M[\frac{b}{k}(u'+\frac{u}{2})\frac{b}{k}(v'+\frac{v}{2})]M^*[\frac{b}{k}(u'-\frac{u}{2}),\frac{b}{k}(v'-\frac{v}{2})]$$

$$e^{\frac{ib^2(u'u+v'v)\Delta}{k}}du'\,dv' \qquad (2)$$

where $\Delta = \frac{1}{a}+\frac{1}{b}-\frac{1}{f}$, f is focus distance of lens. The formula (2) contains aperture function $M(x,y)$ describing the structure of arbitrary complex spatial filter and function F presenting the shape of self-luminous source. Thus we can place the various masks both in the plane $l(x,y)$ and in the source plane.

3. THE EXPERIMENTAL RESULTS

The special experimental systems including two original parts has been designed for experimental test of some results discussed in Section 2 . The first original part of optical system is the field source permitting to change the illumination coherence. Two ways: diaphragming self-luminous sources and laser with phase modulator have been used in our laboratory system. We could change field coherence by using these sources. Special incandescent lamps with conic luminous spiral were used as thermal source. It allowed to achieve two purposes: on the one hand, the source had good brightness, on the other hand, luminous element sizes were sufficiently large (about 3 mm). Such sizes allow to change the coherence within a broad interval. Rough phase screen disposed on the various distance from illumination source (see Fig. 2a) were used for the decrease of spatial coherence.

We noticed above that the optical system was linear relative to the intensity of spatial spectral component for non-coherent illumination. On the basis of this fact, the CTF measurement methods using different test sinusoidal gratings placed into optical system input plane have been designed. CTF measurements were realized by measuring contrast of test grating images.

For the case of our interest (partially coherent illumination) the linear dependence between intensity (or sinusoidal component amplitudes) in input distribution and its image doesn't exist unlike two asymptotic cases of completely coherent and non-coherent illumination . For overcoming these difficulties we propose the methods developed for construction of spatial frequency analyzators. The analyzator operation is based on using moire patterns arising due to superposition of two diffractive gratings rotating in the opposite direction. In our experimental system the following scheme was used. Firstly, the tunable moire pattern was used as input signal with tunable parameters (See Fig.3). Secondly, it was used for spectral analysis of output signal in output plane. Both tunable moire patterns are synchronized in that way that measurement of appropriate spatial component taking scale transformations into account can be done. The rotation of tested lens permitted the two-dimensional CTF measurements (the process of two-dimensional CTF measurement can be automatized by proper synchronization of lens and gratings rotations). After all, two quadrature channels realized by using diffractive gratings with phase quadrature loss (for forming moire patterns) were applied for measurement of CTF phase characteristics (See Fig. 3)).

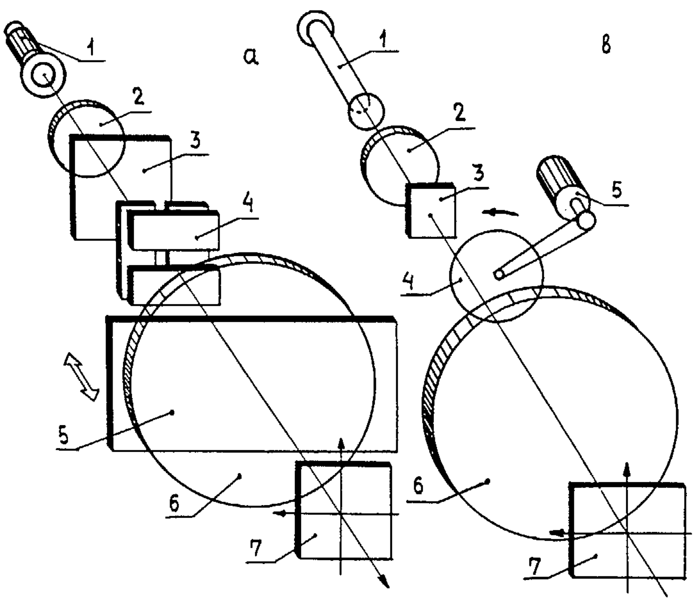

Figure 2: Scheme of construction of illumination source with tunable coherence. The case (a)—scheme with thermal source (1-incandescent lamp, 2-microlens, 3-frequency filter, 4-optical slits, 5-frosted screen, 6-lens, 7-input plane), the case (b)—scheme with laser source (1-laser, 3-spatial filter, 4-rotating diffusor, 5-engine).

Described method was used for CTF measurement. Moire patterns arising out of superposition of diffractive gratings marked on photo plate were as input signals. Similar signals have low contrast and constant component. About

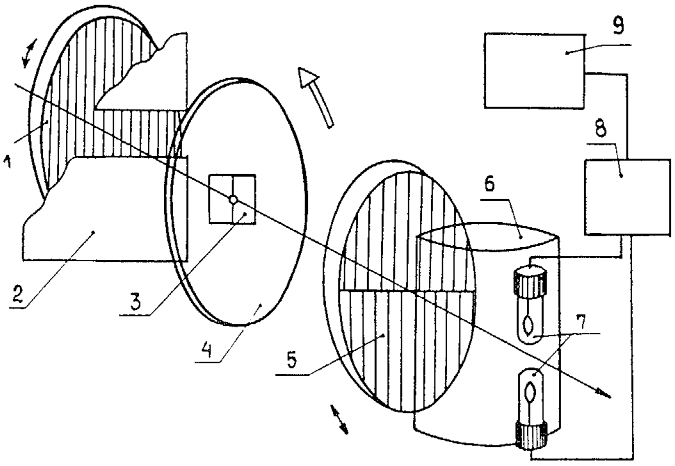

Figure 3: Scheme of optical system CTF measurement for partially coherent illumination (1-input moire pattern, 2-screen, 3-spatial filter, 4-tested lens, 5-analyzing moire pattern with quadrature channels, 6-cylidrical lens, 7-photo-multipliers, 8-analyzator, 9-computer).

that CTF has the width for non-coherent illumination two times larger than for coherent illumination. On the Fig. 4a the CTF normalized modulus as a function of spatial frequency is shown for several source size. The CTF measurement for coherent illumination was realized by using the laser with wave length 0.63 μm. Interference filter was chosen in such a way that the radiation of helium-neon laser passed through the filter. Partially coherent illumination was obtained by using thermal source when optical slits have minimum sizes. The measurement results were similar to experiment with laser for slit sizes $\xi_0 = \eta_0 \approx 10^{-2} mm$. However, the signal-noise ratio in output image decreased due to of photo-multiplier noise. Intermediate case of partially coherent illumination was realized by increasing sizes of slits (curves 2,3 on the Fig. 4a). For this case the signal-noise ratio was the largest, since the brightness of light beam was sufficiently high and interference noise of optical elements was reduced due to decrease of field coherence. Case of non-coherent field corresponded to completely open optical slits, when the frosted screen was placed between slits and lens-collimator. The illumination in output image reduced and measurement accuracy decreased in consequence of light strong scattering on the screen.

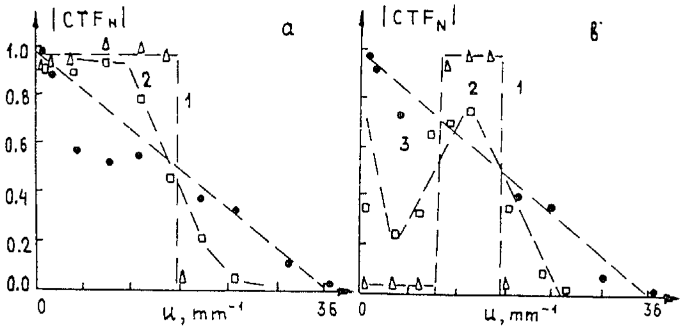

Figure 4: The experimental measurement of CTF modulus as a function of spatial frequency for different source sizes (1-$10^{-2}mm$, 2-$1mm$, 3-$3mm$): a—completely open lens; b—in the presence of low frequency filter.

As follows from comparison of experimental results, the method of CTF measurement by using diffractive gratings is more effective for partially coherent illumination. In comparison with coherent illumination, the partially coherent one gives the considerable reduction of speckle-noise arising on diffractive gratings. With respect to non-coherent illumination, the partially coherent field decreases the sensitivity of optical system to defocusing. In many cases these facts allow to avoid the resolution loss for observation of three-dimensional scenes requiring large depth of optical system sharpness.

As it follows from formulae (1),(2), the optical system defocusing depth depends on illumination field coherence. For incoherent illumination even small defocusing can lead to considerable narrowing system bandwidth. It appears in loss of image clearness, i.e. in decrease of spatial resolution. The dependence of CTF modulus on spatial frequency have been measured for fixed value of Δb and for different illumination source sizes. As measurements show, the defocusing leads to reduction of high frequency range of spatial spectrum. For fixed parameter Δb such reduction increases when approaching the illumination field to completely incoherent field.