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REQUIREMENTS FOR HOLOGRAPHIC PHOTOGRAPHIC MATERIALS,(U)

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by

I. S. Barbanel', E. I. Krupitskiy

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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α α	Nu	Ν	ν
Beta	Β	β	Xi	Ξ	ξ
Gamma	Γ	γ	Omicron	Ο	ο
Delta	Δ	δ	Pi	Π	π
Epsilon	Ε	ε ϵ	Rho	Ρ	ρ ϱ
Zeta	Ζ	ζ	Sigma	Σ	σ ς
Eta	Η	η	Tau	Τ	τ
Theta	Θ	θ ϑ	Upsilon	Τ	υ
Iota	Ι	ι	Phi	Φ	φ ϕ
Kappa	Κ	ϰ κ ϰ	Chi	Χ	χ
Lambda	Λ	λ	Psi	Ψ	ψ
Mu	Μ	μ	Omega	Ω	ω

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Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

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rot	curl
lg	log

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REQUIREMENTS FOR HOLOGRAPHIC PHOTOGRAPHIC MATERIALS

I. S. Barbanel', E. I. Krupitskiy

Holographic devices are finding increasing use in different fields of technology. However, despite a large number of studies, the problem of optimal preparation of holograms has not been resolved. Optimization of the hologram preparation process is broken down into two problems: a) synthesizing the optimal photographic material, b) selecting the optimal recording regime for the hologram in which its parameters will have the best values on the existing photographic material.

It should be mentioned that strict formulation of the synthesizing problem is an extremely complex mathematical problem. Thus, in the present article this problem is analyzed only qualitatively. Nevertheless, the qualitative ideas presented here may be useful in solving the synthesizing problems. Moreover, in the present stage, while there is still no strict solution to this problem, these ideas may also be useful in obtaining photomaterial material. In the present article the following hologram parameters will be considered: a) diffraction effectiveness, b) interference in reduced field, c) nonlinear distortion, d) contrast in reduced image. Let us write the main relationships for the processes of recording and reducing holograms.

We will assume that the referenced and subject waves in the photographing plane can be represented in the form of:

(1)

(a) $$E_{sp} = A(x;y)e^{i\varphi(x;y)},$$

(b) $$E_{on} = A_0 e^{i\varphi_0(x;y)}.$$

Then, exposures during preparation of the hologram are expressed by the relationship:

(2) $$H(x;y) = H_0\left[1 + \frac{2A(x;y)}{A_0}\cos\psi(x;y) + \frac{A^2(x;y)}{A_0^2}\right],$$

where $\psi(x;y) = \varphi(x;y) - \varphi_0(x;y)$; H_0 - exposure created when the reference wave alone acts on the photocarrier.

The amplitude transmission of the prepared hologram can be represented in the form of

(3) $$T(x;y)=F[H(x;y)]=F\left\{H_0\left[1+\frac{A^2(x;y)}{A_0^2}+\frac{2A(x;y)}{A_0}\cos\psi(x;y)\right]\right\},$$

where function F is determined by the type of the characteristic curve of the photocarrier. Expression T(H) is called the optical transmission function (OTF) of the photocarrier.

In reducing the prepared hologram illumination is achieved by the subject or reference beam - (1a) and (1b), respectively. In the first case the subject wave is reduced (holography, interferometry), in the second - the reference wave (optical filtration)*.

[FOOTNOTE: It should be mentioned that in optical filtration the amplitude of the reduced field is proportional to $A^2(x; y)$. END FOOTNOTE]

In reality, since the function of amplitude transmission T(H) can be expanded in the Fourier series with respect to angle ψ:

(4)

$$T(x;y)=C_0(x;y)+2\sum_{n=1}^{\infty}C_n(x;y)\cos n\psi(x;y),$$

where

$$C_n(x;y)=\frac{1}{\pi}\int_0^{\pi}F\left\{H_0\left[1+\frac{A^2(x;y)}{A_0^2}+\frac{2A'(x;y)}{A_0}\cos\psi\right]\right\}\cos n\psi\,d\psi,$$

then we get:

(5a)

$$E_{\text{восст пр}}=C_0A_0e^{i\varphi_0}+A_0C_1e^{i\varphi(x;y)}+A_0C_1e^{-i[\varphi(x;y)-2\varphi_0]}+\ldots$$

$$E_{\text{восст оп}}=C_0A_1(x;y)e^{i\varphi(x;y)}+A_1C_1e^{i\varphi_0}+\ldots$$

(5b)

Comparison of (5) and (1) shows that only the second components are useful:

$$E_{\text{вых пр}}=A_0C_1(x;y)e^{i\varphi(x;y)};$$

$$E_{\text{вых оп}}=A_1(x;y)C_1(x;y)e^{i\varphi_0}.$$

From relationship (5a) and (5b) it is apparent that the parameters of the reduced image can be characterized with any degree of accuracy by a set of coefficients C_n, which depend on the form of the OTF of the photocarrier (function F), amplitude distribution of the subject beam with respect to coordinates, relationship between the amplitudes of the subject and reference beams.

Now let us see what the OTF of the photocarrier must be in order to create a hologram with optimal parameters.

Diffraction Effectiveness

Diffraction effectiveness ξ is determined by the expression:

$$\xi = \frac{\Phi_1}{\Phi_\Sigma},$$

where [illegible] is the light flux which corresponds to the first diffraction order [illegible] – the light flux incident on the hologram.

From relationships (5a) and (5b) it follows that Φ_1 is proportional to C^2_1, and thus diffraction effectiveness grows as coefficient C_1 increases. Consequently, we can assume that the best OTF has a rectilinear shape (see the figure).

If the range of exposure change lies within the limits of the linear portion of the characteristic (regime without cut-off), then

$$C_1' = 0{,}25 \text{ and } \xi' = 6{,}25\%.$$

Greater diffraction effectiveness can be achieved if we use one- and two-sided (see figure) cut-off. Here we get, respectively:

$$C_1'' = 0{,}3,\ C_1''' = 0{,}31;\ \xi'' = 9\%,\ \xi''' = 9{,}65\%.$$

With a two-sided cut-off we get the so called binary hologram. In working with the linear characteristic and when all of its linear portion is used, the slope of the OTF toward axis H does not affect the diffraction effectiveness value.

It should also be mentioned that the linear portion of the T(H) characteristics determines the dynamic range of change in the amplitudes of the reduced field. If we are to be able to use the advantages of the cut-off regime then the OTF must have an AB segment of sufficient length (see the figure). However, in registering with a cut-off, in view of the nonlinearity of the registering process, nonlinear distortion develops. (Its magnitude depends on the coefficient of expansion (4) - C_2: C_3, etc.).

Interference In Reduced Fields

Interference in the reduced image is the result of three factors: granularity of the layer, scattering within the layer, and uneven thickness of the carrier ("phase interference"). The effect of granularity on image quality can be determined by the Goodman formula [1]:

(7) $$I_m = \frac{A_e S(1-C_0)C_0 I_0}{\lambda^2 z^2},$$

where I_m is noise intensity at distance z from the hologram: λ - wavelength of illumination source; I_0 - illumination intensity; A_e - mean area of emulsion grain; S - area of hologram.

Then the "signal/noise" ratio with only the granularity considered in the case where a hologram of a quasi-point object is reduced, is expressed by the formula:

(8) $$\eta = \frac{C_1^2}{C_0(1-C_0)}.$$

In order to insure the maximum "signal/noise" ratio determined by (8) it is also desirable to have an OTF of linear shape, since in this case coefficient C_1, which determines the useful signal, increases considerably in comparison to the case of the nonlinear OTF, while $C_0(1 - C_0)$, which determines interference, remains virtually unchanged. The maximum "signal/noise" ratio is achieved in this case by using the cut-off regime.

To reduce "phase interference" during the preparation of photocarriers designed for the production of holograms special measures must be taken to assure stability in the thickness of the carrier. We know that according to this criterion photoplates produced on glass of high optical properties have the best indicators. Although the phase interference of the holograms can be reduced by using immersion during reduction, this method is quite inconvenient in practice.

Nonlinear Distortion

Nonlinear distortion can be broken down into two components: a) distortion of amplitude distribution in diffracted beam of first order (subject wave); b) superimposition on useful image of diffracted beams of higher orders. In the hologram reduction process cases are possible where only the first component or where both components are present.

Minimum amplitude distortion is achieved in two cases: a) in preparing holograms with a diffuser, in which case amplitude A of the subject beam is independent of the space coordinate and distortion does not develop; b) in using the OTF of linear shape, where nonlinear distortion is absent if registering is done in the regime without cut-off, since $C_n = 0$ for n = 2, 3, 4...

If the cut-off regime is used, which leads to a significant increase in diffraction effectiveness, nonlinear distortion grows sharply. This cannot be tolerated when precise reduction of the field is required. However, for holograms with diffusion this regime is very advantageous, since it results in increased diffraction effectiveness without amplitude distortion.

To minimize amplitude distortion a photocarrier must be prepared which has a OTF with a linear section of maximum length to assure linear registration of field amplitude which vary within a broad range.

In preparing holograms with a diffuser it is more convenient to use a photocarrier with the OTF shown in the figure, since this assures a cut-off regime and maximum diffraction effectiveness with no amplitude distortion.

The second component of linear distortion - superimposition of higher diffraction orders - leads to a redistribution in field amplitudes in the first diffracted beam. The analytical expression for field amplitudes of higher orders is provided by coefficients $C_n (n \geqslant 2)$.

In using the linear characteristic and working within the limits of the linear portion, nonlinear distortion is absent (since in this case $C_n = 0$ for $n \geq 2$).

Contrast of Reduced Image

High contrast is important in recording weak signals, where the amplitude of the subject beam is low. In this case the optimal photocarrier is one with maximal OTP transconductance in the small exposure range. If simultaneously we limit the distortion level of the reduced image, then the photocarrier must have a OTP of linear shape in the range of small exposures. The form of the OTP in the large exposure range for the given case is not important.

Sensitivity of Photographic Material

Sensitivity is a characteristic of the photographic material itself, not of the hologram. High sensitivity is particularly important in the case of a weak signal. A resume of recommendations of selecting the form of the OTP of the photocarrier as a function of hologram requirements is presented in the table.

Conclusions

Hologram parameters, optimized by selection of the OTF of the photocarrier, are contradictory. As a rule it is not possible on one photocarrier to achieve the optimum of all hologram parameters. Therefore we recommend three main types of OTF: 1) OTF with high transconductance in the range of small exposures- for the case of a weak signal; 2) piece-wise linear OTF - to achieve maximum diffraction effectiveness; 3) OTF with an extended linear portion - to assure a large dynamic range.

Consequently, the linear OTF is optimal for many hologram parameters, although the length and slope of the linear portion are changed in keeping with the specific individual problem encountered in registering holograms.

Specifically, in registering several holograms on a single photocarrier it is also convenient to have a photocarrier with a OTF which has a maximal linear section along the H-axis, since this will assure optimal registration of the field with respect to many parameters with a broad range of change in amplitudes.

Electrotechnical Institute of Communications

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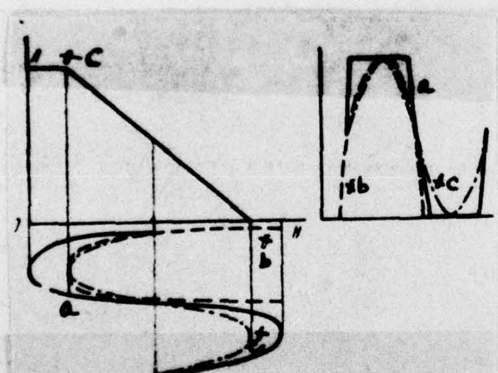
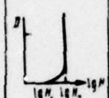


Figure. Regime for registering amplitude holograms with cut-off: two-sided (a), one-sided (b), and without cut-off (c).

Table.

(1) № пп.	(2) Вид параметра	(5) Требования к характеристикам фотоматериала и режиму записи				(8) Примечания
		(4) ОПФ	(5) Характеристическая кривая	(6) режим записи	(7) прочие требования	
1	(9) Дифракционная эффективность			(10) С двухсторонней отсечкой	—	(11) Максимальная эффективность — 10% (без отсечки — 6,25%)
2	Отношение «сигнал — шум» (12)			То же (13)	(14) Минимальные размер и рассеяние. Постоянство оптической толщины фотоматериала	При выборе ОПФ учитывается лишь шум за счет зерен эмульсии
3	(16) Нелинейные искажения: а) амплитудные искажения в первом порядке			(17) Без отсечки	—	(18) При голографировании с рассеивателем и изготовлением голограмм фаз. объектов отсутствуют
	(19) б) уровень высших порядков			(20) То же	—	—
4	(21) Чувствительность			(22) На начальном линейном участке $T(H)$	—	(23) Важна для случая слабого сигнала
5	(24) Контраст восстановленного изображения			То же (24A)	(25) Минимальные размер зерен и рассеяние	(26) 1. Важен для случая слабого сигнала 2. Важна наиболее протяженная ЧКХ
6	(27) Разрешение пространственных частот	—	—	—	(28) То же	(29) Важна наиболее протяженная ЧКХ

(See next page for caption.)

Table. Conditions for obtaining best basic parameters for thin-layer amplitude holograms.

Key: (1) No. in order, (2) Parameter, (3) Requirements for characteristics of photographic material and registering regimes, (4) OTF, (5) characteristic curve, (6) registering regime, (7) other requirements, (8) Notes, (9) Diffraction effectiveness, (10) With two-sided cut-off, (11) Maximal effectiveness - 10o/o (without cut-off - 6.25o/o), (12) "Signal/noise" ratio, (13) The same, (14) Minimal dimension and scatter. Constancy of optical thickness of photographic material, (15) In selecting OTF only interference resulting from emulsion grains is considered, (16) Nonlinear distortion: a) amplitude distortion in first order, (17) Without cut-off, (18) In holography with diffusion and preparation of phase holograms there are no objects, (19) b) level of higher orders, (20) The same, (21) Sensitivity, (22) On initial linear portion T(H), (23) Important for weak signals, (24) Contrast of reduced image, (24a) The same, (25) Minimal grain dimension and diffusion, (26) 1. Important for weak signal. 2. Longest frequency-contrast characteristic is important, (27) Resolution of three-dimensional frequency, (28) The same, (29) The longest frequency-contrast characteristic is important.

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